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Stewardship Considerations for Nevada FFACO Corrective Action Units Closed through the EM NV Soils Activity based on Monitoring of Radionuclide Transport

Prepared by
Jenny B. Chapman and Julianne J. Miller

Submitted to

Environmental Management Nevada Program
U.S. Department of Energy
Las Vegas, Nevada

February 2021

Publication No. 45295

Nevada System of Higher Education

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Division of Hydrologic Sciences
Desert Research Institute
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EXECUTIVE SUMMARY

Years of monitoring at six U.S. Department of Energy Soils Activity plutonium dispersal experiment sites provided data on the transport of radionuclides at and from these locations. The regulatory closure process followed for the Smoky Site (a site that also includes an aboveground nuclear test), Project 57, Plutonium Valley, and Clean Slates I, II, and III was based on the analysis of contaminant concentration levels that lead to acceptable levels of risk. A consequence of this approach is that after clean-closure and closure-in-place actions, radionuclide contaminants remain as the sites enter post-closure. Describing the fate and transport of these contaminants based on monitoring and evaluation provides information to land managers as they develop stewardship plans and procedures to minimize human exposure to the radionuclides, optimize future monitoring efforts, and communicate site conditions and controls.

The primary focus of the monitoring conducted at the Smoky Site and Plutonium Valley was the movement of radionuclides in sediment entrained in episodic surface-water flow through ephemeral channels. At the Clean Slate and Project 57 sites, monitoring focused on the wind-borne movement of radionuclides in soil particles being suspended in the air or saltating (i.e., bouncing) along the ground surface. All study sites had meteorological equipment and soil sensors. The Smoky Site and Plutonium Valley included flumes and fluvial sediment sampling. The Clean Slate and Project 57 monitoring stations included airborne particle sensors and samplers, as well as saltation particle sensors and samplers. Pressurized ion chambers at Clean Slates I and III, and thermoluminescent dosimeters at Project 57 measured gamma radiation. Most of the monitoring stations began collecting data in 2011, although two stations were running at Clean Slate locations as early as 2008. The monitoring stations were removed from the Smoky Site and Plutonium Valley in 2019 and from Project 57 in late 2020, whereas monitoring is expected to continue through at least 2021 at the Clean Slate sites. In addition to the site-specific research, the effect of wildfire on soil movement was investigated at three uncontaminated analog sites that experienced fires, which corresponded to the Great Basin, Mojave Desert, and transition ecoregions. Runoff and water erosion, wind erosion, and revegetation were evaluated over a three-year period at the burned and corresponding unburned surfaces. Finally, physiochemical stabilizers and mechanical stabilization methods were evaluated in a literature review for their possible application to the contamination sites.

Conditions were identified at all the evaluated Soils Activity sites that would allow radionuclide transport and at many of the monitoring locations, such transport was directly observed. These conditions are intermittent, with long periods of stability between brief but sometime intense transport events. Movement of radionuclide-contaminated dust was observed to occur by advection of small suspended particles in air and by saltation of larger particles along the ground surface. Wind speeds greater than 15 miles per hour (mph) are primarily responsible for dust movement. Sustained winds greater than 15 mph at the monitoring sites are from the north, northwest, or south more than 85 percent of the time, so the long-term effect will be the spread of radionuclides to the south and north of the contamination areas. Spring has the highest frequency of winds exceeding 15 mph and high winds are most frequent in the afternoon. Dry soil moisture and relative humidity conditions promote dust movement, so dust storms are also frequent in summer, despite generally slow winds during that season. Gross alpha, plutonium-239+240 ($^{239+240}$Pu), plutonium-238

(^{238}Pu), and americium-241 (^{241}Am) concentrations were found on suspended dust particles collected from air filters and on saltating particles collected from passive, near-ground-surface traps. Radionuclide concentrations were observed to increase dramatically during earth-disturbing activities at Clean Slates II and III.

Water moving through ephemeral channels entrains sediment and transports it downstream. Flow velocities of three feet per second (fps) or higher are needed for sediment movement of typical desert soil particle sizes. The flow events capable of sediment transport are the result of high-intensity precipitation events, which primarily occur during the summer monsoonal period. Daily precipitation thresholds of 0.03 inches per day (in/day) and 0.9 in/day are identified as thresholds that usually (>50 percent of days) generate runoff greater than 0 fps and 3 fps, respectively. The intensity of rainfall is another important factor for runoff. An intensity of 0.1 inch in 10 minutes consistently creates measurable flow at the Smoky Site and Plutonium Valley. Streamflow was recorded 57 times at the Smoky Site between 2011 and 2018, and 9 times at Plutonium Valley between 2011 and 2019. Based on analysis of precipitation gage data from the NNSS, it is likely that runoff will occur 60 to 70 times a decade, with flow greater than 3 fps occurring one to two times per decade. Channel bed samples at the Smoky Site and Plutonium Valley contained ^{241}Am, ^{238}Pu, and $^{239+240}$Pu after flow events and the smaller particles had the highest concentrations.

The effect of wildfire on soil erosion varied with ecoregion. The greatest post-fire erosion risk was associated with the Great Basin Desert ecoregion, where wind erodibility substantially increased when large plant undercanopy areas were exposed after shrubs and trees burned. Water repellency and greater runoff were observed for burned soils. Within a couple of years after a fire, the wind erodibility and runoff potential were similar for burned and unburned surfaces in the Mojave Desert and transition ecoregions. Vegetation at the study sites in all ecoregions did not recover to pre-burn levels within the three-year observational period and post-fire invasive species were observed.

Revegetation of disturbed landscapes improves long-term stability by reducing both water and wind erosion, although it is a slow process that benefits from supplemental irrigation. Mechanical stabilization methods, such as mulch and riprap, are likely to be most applicable for controlling radionuclide movement by precipitation runoff. Physiochemical stabilizers, such as clays and polymers, can help control dust suspension and saltation, although there are also mechanical approaches for reducing wind shear by increasing surface roughness. Without ongoing maintenance, the effectiveness of mechanical and physiochemical stabilization methods can be expected to diminish or fail within several years, and therefore they are best used to achieve short-term erosion control.

The studies of conditions leading to contaminant migration at the Soils Activity sites can be used to guide management decisions that will maintain personnel exposure to radionuclides at levels as low as reasonably achievable (ALARA). The time personnel spend on-site should be minimized when winds exceed 15 mph, and therefore planned activities should avoid spring, the afternoon, and the July and August period of the North American monsoon. Activities in channels downstream of contamination areas should be suspended after precipitation events near and above a threshold of 0.1 inch per 10 minutes until radiological surveys can be performed. Runoff control hydraulic structures, such as the detention basin in Plutonium Valley, require infrequent maintenance to remain effective for

controlling sediment transport. Communication plans for each site could be used to identify the ALARA controls, identify activities allowed and prohibited, and explain the known and anticipated distribution of radionuclides.

Although minimal maintenance and monitoring is required for the closed Soils Activity sites, there may be conditions in the future that lead to interest in short- or long-term monitoring. Lessons learned from the years of monitoring at the Smoky Site, Plutonium Valley, Project 57, and Clean Slate sites can be applied to such efforts. Monitoring of the physical environment should include event-based monitoring of bedload material in channels after runoff events. Rainfall intensity should also be monitored to identify these events, which are associated with a threshold of 0.1 inch per 10 minutes. Event-based monitoring of air quality should also be considered during site-disturbing activities and after wildfires. Analysis of suspended dust collected with glass-fiber filters should focus on gross alpha and alpha spectroscopy in conjunction with meteorological data. Infrequent but periodic surveys of radionuclide concentrations in the predominant downwind directions outside the contamination areas will be useful for assessing land-use plans adjacent to sites and responding to concerns potentially raised in the future. Monitoring human activities both within the contamination areas and in the nearby areas outside of the contamination areas, as well as monitoring the effectiveness of institutional controls, will complement the surveillance of the physical environment, given the closure conditions are specific to human exposure assumptions.

Events that could cause enhanced radionuclide migration from closed Soils Activity sites include natural processes of extreme wind, rainfall, and wildfire events and human disturbance of the ground surface. Event-based monitoring can be used for these conditions, and physicochemical and mechanical stabilization techniques may be useful for short-term mitigation. Revegetation of disturbed areas using enhancement techniques to promote success is the method best-suited to reducing the erosion of contaminated lands in the long-term.

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The commitment of the U.S. Department of Energy (DOE) Environmental Management Nevada (EM NV) to protecting human health and the environment at lands with long-lived radionuclide contamination made this work possible. The engagement of EM NV manager-scientists Rob Boehelcke, Kevin Cabble, and Tiffany Gamero and their many contributions are gratefully acknowledged. The vision of David Shafer was a primary driver for understanding the importance of long-term environmental monitoring data in developing long-term stewardship plans. Monitoring in remote areas for long periods of time requires quality equipment design and deployment, as well as reliable recording and data transmission capabilities. Greg McCurdy, George Nikolich, and Scott Campbell were responsible for establishing the design and construction of the many monitoring stations at the Soils Activity sites. The reliable operation of the sites required a cadre of skilled and dedicated scientists, including Greg McCurdy, George Nikolich, Scott Campbell, Steve Mizell, Lynn Karr, Kevin Heintz, and Ken Giles. During most of the monitoring period, Craig Shadel managed the radionuclide samples and reported and interpreted the laboratory results. In more recent years, these responsibilities were handled by John Goreham. Austin Chapman prepared many of the data appendices and figures for inclusion in the annual reports. Annual reports interpreting the environmental and radionuclide data, many of which were prepared by teams led by Steve Mizell, are critical to making the results accessible for this summary and for future workers. Collaborations with the EM NV contractor were vital for safe and efficient on-site work and for facilitating some of the radionuclide analyses. Although many EM NV contractor personnel provided support, particular acknowledgement goes to Patrick Matthews, Mark Burmeister, and Milinka Watson-Garrett. The multiyear evaluation of wildfire effects required scientists from a wide array of disciplines to conduct intensive investigations during sometimes harsh conditions, including Michael Clifford, Vicken Etyemezian, George Nikolich, Mary Cablk, Lynn Fenstermaker, and Rose Shillito. The authors gratefully acknowledge that all of the information summarized in this report exists because of the work of the people named above.

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LIST OF ACRONYMS

ALARA	as low as reasonably achievable
CAA	Corrective Action Alternative
CAS	Corrective Action Site
CAU	Corrective Action Unit
CEMP	Community Environmental Monitoring Program
DOE	Department of Energy
DRI	Desert Research Institute
EM NV	Environmental Management Nevada Program
FAL	final action level
NV FFACO	Nevada Federal Facility Agreement and Consent Order
NNSS	Nevada National Security Site
NTTR	Nevada Test and Training Range
PIC	pressurized ionization chamber
REOP	Real Estate/Operations Permit
RMA	radiological materials area
TTR	Tonopah Test Range

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INTRODUCTION

This report provides an overview of the movement of radionuclide-contaminated soils as understood from the environmental monitoring activities performed by Desert Research Institute (DRI) at locations of former nuclear experiments and tests. This information is summarized to support land managers in their stewardship of these sites. Considerations for long-term management and monitoring are based on the site data and findings, as well as related research of wildfire effects on analog sites and of stabilization technologies.

The Soils Activity category of Corrective Action Units (CAUs) addressed by the U.S. Department of Energy (DOE) through the Nevada Federal Facility Agreement and Consent Order (NV FFACO) includes sites with surface and shallow subsurface soil contamination resulting from nuclear experiments and testing at the Nevada National Security Site (NNSS), Nevada Test and Training Range (NTTR), and the Tonopah Test Range (TTR). Corrective actions at these sites were determined using a risk-based strategy that assessed potential effects on human and environmental receptors by comparing contamination levels to risk-based action levels (DOE, 2014). In some cases, contaminants were either present at concentrations lower than the final action level (FAL) or concentrations were reduced below that level during remediation such that a Corrective Action Alternative (CAA) of clean closure, as defined by the NV FFACO, was implemented. In other cases, contaminants remained at concentrations above the FAL and the corrective action implemented was a closure in place with various administrative controls, which always included a use restriction.

Environmental risk is calculated based on a contaminant source, a receptor, and a pathway for the contaminant to reach the receptor. The Soils Activity used radiological dose as a surrogate for radiological cancer risk (DOE, 2014). All radiological contaminant action levels for the Soils Activity are based on a 25 millirem per year (mrem/yr) dose constraint. This level is consistent with the DOE dose constraint for the release of a property for future use, as established in DOE Order 458.1 (DOE, 2011).

The development of the FAL from the 25 mrem/yr dose constraint involves assuming an exposure scenario. A critical factor in the exposure considerations for the Soils Activity sites is the amount of time assumed for exposure. For example, a ground troop scenario was used for two of the Clean Slate sites at TTR that assumed 1,008 hours of exposure to contaminated soil in a year, whereas an occasional use scenario of 80 hours on site per year for five years was used for the radiological action level at the Smoky Site contamination area on the NNSS (DOE, 2015).

Based on the NV FFACO regulatory process, even a clean closure site, as well as closure-in-place sites, can have radiological contaminants of concern remaining in concentrations above background after the site enters post-closure. Understanding the fate and transport of radiological contaminants is important for long-term stewardship of the Soils Activity sites. The Environmental Management Nevada Program (EM NV) supported DRI for monitoring and evaluations of several key Soils Activity sites to determine if and under what conditions radionuclides are transported through the environment.

Under the Soils Activity, EM NV brought 28 CAUs to closure, which contain over 100 Corrective Action Sites (CAS). Nine of the CAUs included plutonium dispersion sites, eight were collections of atmospheric nuclear test sites, six included craters created by nuclear tests, and the remainder were sites with other types of miscellaneous surface and near-surface contamination. The six CAUs selected by EM NV for focused monitoring and evaluation all included plutonium dispersion sites, and one was also the location of an atmospheric nuclear test. Radionuclide transport by wind was of concern at all six sites, but it was a particular focus of investigation at Clean Slates I, II, and III at TTR and Project 57 at the NTTR. Waterborne transport of radionuclides through ephemeral drainages was similarly possible at several sites, but it was addressed by specific instrumentation at Smoky Site and Plutonium Valley on the NNSS.

This report summarizes the EM NV/DRI work with the intent of conveying this information to the long-term land managers who will assume responsibility as EM NV completes its environmental restoration mission. A brief description of each of the six evaluated Soils Activity sites is provided, which is followed by a discussion of the findings regarding radionuclide transport learned at the sites. The implications of these findings are examined for site management, routine monitoring, and monitoring during potentially adverse events. Possible mitigation actions are also identified. The appendices provide a more detailed examination of the conditions under which radionuclide transport occurs at these sites.

INVESTIGATIONS OF SOIL ACTIVITY SITES AND RELATED STUDIES

On behalf of the EM NV commitment to protecting human health and the environment, radionuclide transport investigations were conducted at one aboveground nuclear test location known as the Smoky Site (where plutonium dispersal experiments were also carried out) and the five plutonium dispersal sites known as Project 57, Plutonium Valley, and Clean Slates I, II, and III (Figure 1 and Table 1). Investigations into surface stabilization techniques and the effect of wildfires were also conducted. Each of these is briefly outlined in this section. Appendix A provides a bibliography of the publications that contain the investigation designs, data, and interpretations. The common goal of these investigations was to determine if and under what conditions radionuclide transport was occurring to inform site management and stewardship decisions.

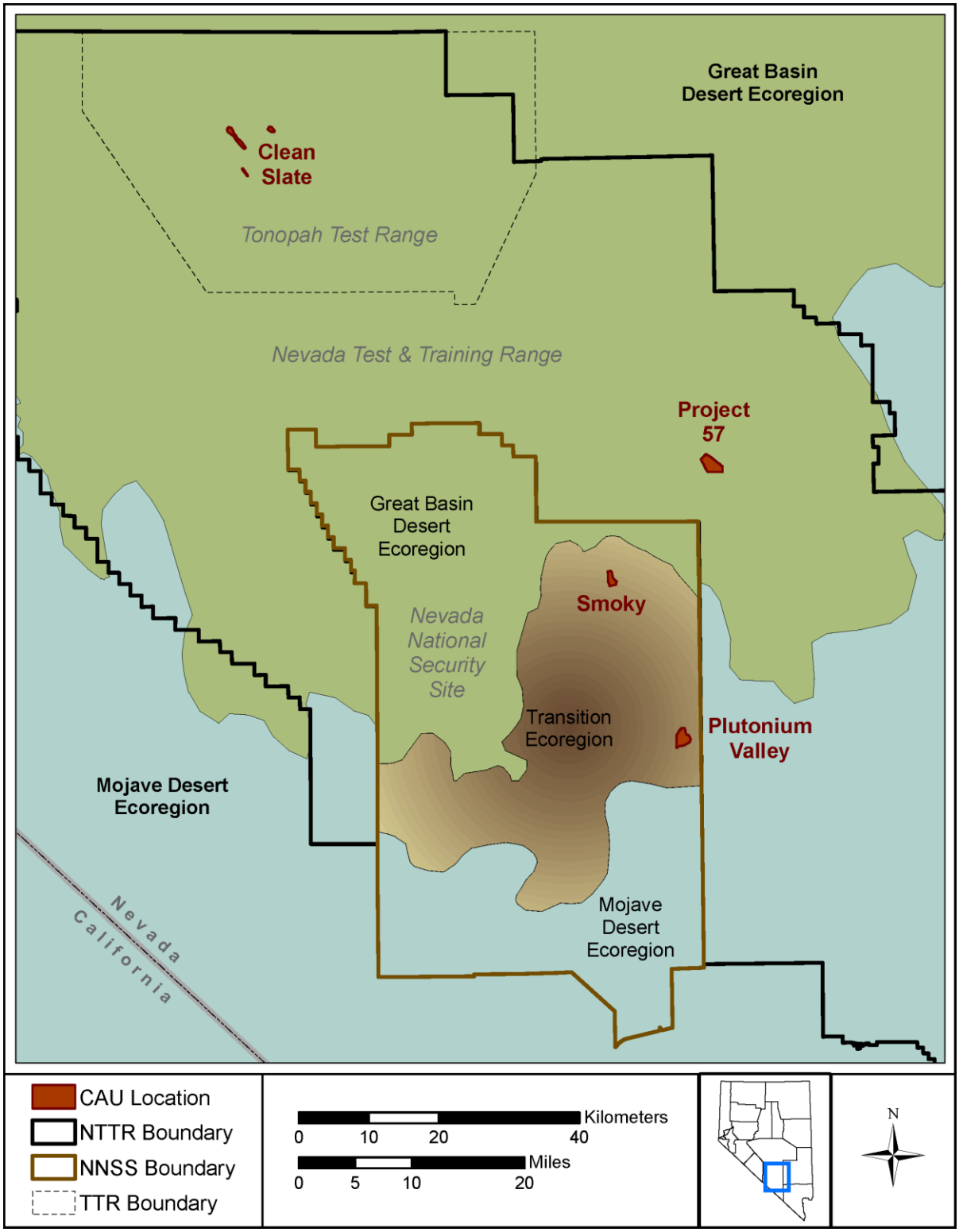

Figure 1. Locations of the Soils Activity sites monitored to evaluate radionuclide transport behavior. The ecoregions are identified by their background color, although the transition ecoregion has not been defined outside the NNSS (Ostler *et al.*, 2001; https://geospatial.tnc.org/datasets/7b7fb9d945544d41b3e7a91494c42930_0?page=11).

Table 1. General monitoring measurements for the Soils Activity monitoring locations. Appendix B lists the sensors and data.

Site	Pathway Focus	Meteorological & Soil Sensors	Flume	Fluvial Sediment Sampling	Airborne Particle Sensors	Airborne Particle Sampler	Saltation Sensors	Saltation Sampler	PIC	TLD
Smoky	Water	✓	✓	✓	NA	NA	NA	NA	NA	NA
Plutonium Valley	Water & Air	✓	✓	✓	✓	NA	NA	NA	NA	NA
Clean Slate I	Air	✓	NA	NA	✓	✓	✓	✓	✓	NA
Clean Slate II	Air	✓	NA	NA	✓	✓	✓	✓	NA	NA
Clean Slate III	Air	✓	NA	NA	✓	✓	✓	✓	✓	NA
Project 57	Air	✓	NA	NA	✓	✓	✓	✓	NA	✓

NA = not applicable

PIC = pressurized ion chamber.

TLD = thermoluminescent dosimeter.

Smoky Site Contamination Area

The Smoky Site is located in northwestern Yucca Flat on the NNSS. An atmospheric nuclear test (SMOKY) and three safety experiments of nuclear devices were conducted at this site. Meteorological conditions at the time of the experiments dispersed radionuclides (such as plutonium isotopes) to the north, but later observations of radionuclide-contaminated soils in channels traversing and south of the site indicate that rainfall-generated runoff is moving contaminated material downstream. In 2011, DRI began monitoring the site for EM NV with the objectives of determining the contribution of rainfall runoff to ongoing contaminant migration through ephemeral channels, the meteorological conditions that result in contaminant movement, and the particle size of the material being moved. An environmental monitoring station with meteorological and soil moisture instrumentation was installed. Monitoring runoff was addressed by installing a Parshall flume to measure the depth of flow and thus discharge. Flow velocities were calculated from the cross-sectional area of the channel and the discharge. Bedload samples were collected from the channel after major flow events and analyzed for radionuclides. Monitoring was discontinued and the monitoring equipment was removed in October 2019.

Plutonium Valley

Plutonium Valley is located in the eastern part of the NNSS and was the location of four safety tests of nuclear devices. These tests, which did not include nuclear detonations, resulted in extensive contamination on the ground surface. Multiple surveys conducted over several years have not only detected radionuclides in a channel traversing the site, but also the downgradient migration of these radionuclides in the channel, which indicates

contamination transport during runoff events. In 2011, DRI installed two meteorological and soil moisture monitoring stations with aerosol particle counters and a fluvial sediment sampling station in Plutonium Valley. The purpose of the monitoring was to assess the potential for radionuclide-contaminated soil to be transported from the site during wind events and storm runoff, and to determine the meteorological conditions that cause this transport. The fluvial sediment station included passive traps for bedload material and a sampling pump that would activate to collect suspended sediment when sufficient flow was present in the channel. Monitoring was discontinued and the monitoring equipment was removed in October 2019.

Clean Slates I, II, and III

The Clean Slate sites are located in Cactus Flat on the TTR. The tests conducted at these sites subjected nuclear devices to simulated storage or transportation accidents, resulting in the dispersal of radionuclides across the land surface (there were no nuclear detonations). In 2008, DRI deployed two monitoring stations at TTR on behalf of the Soils Activity. Additional stations were added during subsequent years and there are five stations at TTR as of 2020. Some stations have been moved because of site activities. The sites were monitored prior to, during, and subsequent to remediation activities conducted from 2017 to 2019. The primary objective of the monitoring stations is identification of the wind-borne transport of radiological contaminants and the weather conditions under which it occurs. The stations include a continuous, low-volume air sampler that collects suspended particulate matter, aerosol particle counters, sensors to record saltating particles, traps to collect saltating particles, and meteorological and soil moisture monitoring equipment. Three of the stations are also equipped with pressurized ionization chambers (PICs). Not all instruments have been in use for the entire time. Monitoring is expected to continue for at least two years after the completion of remediation activities, with monitoring through the end of calendar year 2021. Monitoring from September 30, 2020 forward is managed by the DOE Office of Legacy Management, the site steward from that date.

Project 57

The Project 57 site is located in western Emigrant Valley on the NTTR. The experiment dispersed plutonium to evaluate its immediate distribution and long-term redistribution properties, as well as decontamination, survey, and biomedical techniques. The device used at this site did not create a nuclear detonation. In 2011, DRI established two monitoring stations for EM NV adjacent to the fence line within the contamination area. Pathways designated as radiological materials areas (RMAs) were surveyed through the contamination area to the fence. The objectives of the monitoring at this site were to identify the meteorological conditions that result in airborne soil particle redistribution and the concentrations of radiological contaminants entrained with the airborne soil. The stations included a continuous, low-volume air sampler; thermoluminescent dosimeters; aerosol particle counters; sensors to record and traps to collect saltating particles; and meteorological and soil moisture monitoring equipment. Not all instruments were in use for the entire time. The station locations were moved in 2015 to better align with the predominant wind patterns determined from the prior monitoring. Monitoring continued through the construction of a cap over the high-contamination area and was discontinued, and the monitoring equipment removed, in October 2020.

Surface Stabilization Research

In 2014, a literature review was published that evaluated soil stabilization methods for minimizing erosion. This review also presented the significant physical and chemical properties of soil used to assess the stabilization methods and identified evaluation criteria for applying the stabilization approaches to the NNSS. The evaluation included both physiochemical stabilizers (e.g., clay mineral additives and polymer products) and mechanical stabilization methods (e.g., compaction and revegetation). Implementation of soil stabilization efforts at the NNSS were also reviewed.

Wildfire Research

To determine the potential effects of wildfire on the transport of contaminated soils, three uncontaminated analog sites were evaluated for three-year periods. The three sites evaluated were the Gleason Fire near Ely, Nevada, in the Great Basin ecoregion; the White Rock Fire near Mesquite, Nevada, in the Mojave Desert ecoregion; and the Jacob Fire near Hiko, Nevada, in a transitional ecoregion between the Great Basin Desert and Mojave Desert. These three sites represent the different ecoregions of the NNSS, NTTR, and TTR. Samples and data were collected pre-fire at the Gleason Fire (which was a controlled burn) and at various times post-fire at all sites. The processes evaluated were runoff and water erosion, wind erosion, and revegetation.

FINDINGS REGARDING TRANSPORT OF RADIOLOGICALLY CONTAMINATED SOILS AT NV FFACO SITES

The primary contaminants of concern at the investigated Soils Activity sites are isotopes of plutonium, uranium, and americium. These radionuclides tend to attach to small soil particles, and therefore wind-suspended dust and rainfall runoff can transport these contaminants. Monitoring by EM NV addressed both of these pathways and evaluated the effects of land disturbance, wildfire, and stabilization approaches on transport processes.

Conditions that would allow radionuclide transport were identified at all of the Soils Activity sites evaluated and such transport was directly observed at many of the monitoring stations. However, those conditions are intermittent, with long periods of stability between brief but sometimes intense transport events. This creates challenges for measuring infrequent events and challenges for understanding the incremental changes that may be individually small but aggregate over time.

At most Soils Activity sites, transport processes by both air and water are active, although transport is dominated by one pathway for a given site. Evaluation of the Project 57 and Clean Slate sites focused on airborne radionuclide migration. The stations at Plutonium Valley monitored airborne dust migration, but they did not include air sampling. Both the Plutonium Valley and Smoky Site monitoring stations were designed to gather information on waterborne transport.

Airborne Transport of Radionuclides

Airborne contaminant migration has been observed at all sites with air samplers (Clean Slate and Project 57 sites). These observations have been analyzed with detailed measurements of atmospheric conditions and dust movement. Given the importance of atmospheric and soil conditions for radionuclide transport from the Soils Activity sites,

meteorological and environmental monitoring equipment was deployed at each monitoring station. Appendix B provides period-of-record summaries of the measured conditions. Appendix C provides an in-depth presentation of the wind conditions and particle movement at the monitored sites. A summary of findings is presented below.

How does the airborne transport of radionuclides occur?

Movement of radionuclide-contaminated dust and soil has been observed to occur at the sites through the advection of small suspended particles in the air and the saltation of larger particles along the ground surface. Suspended radionuclides have been captured on the filters of continuous air samplers and saltating particles have been found in near-ground passive traps. Saltating particles are relatively large (50 micrometers [µm] to 500 µm in diameter) and essentially bounce along the land surface as wind-generated shear stress dislodges them (Figure 2). The height, duration, speed, and trajectory of these particles depend on wind speed and particle mass, but generally a saltating particle will be airborne for a short distance of at most a few meters before it falls back to the ground. The impact of saltating particles dislodges smaller particles that are then ejected into the air and transported by wind suspension. Suspended particles smaller than 20 µm in diameter can be entrained in the air and transported over long distances, and particles smaller than 10 µm (PM_{10}) are small enough to be considered easily inhalable by humans.

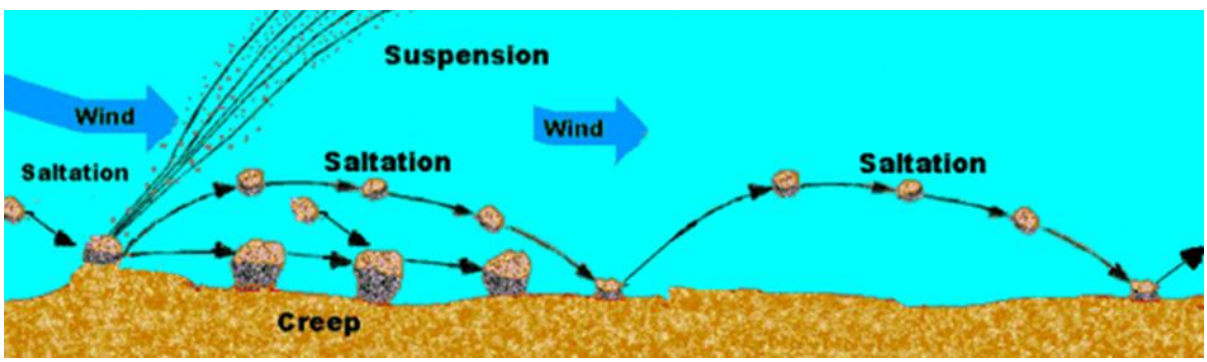

Figure 2. Diagram of the processes of soil particle movement by air. The suspension of smaller particles ejected by the impact of a particle landing after saltation is depicted on the left. (The Weather Doctor, http://www.islandnet.com/~see/weather/elements/dustwind.htm, accessed December 7, 2015.)

What conditions cause the airborne transport of radionuclides at the sites?

Wind-suspended dust concentrations in the air remain low at these sites until the wind speed is greater than approximately 15 mph (Figure 3). Generally, dust concentrations increase at an exponential rate with increasing wind speed above 15 mph, but a decrease in concentration at wind speeds greater than 30 mph is sometimes observed, suggesting an upper limit to the supply of suspendable dust at any given time. Higher relative humidity and soil moisture, which are often associated with recent rainfall events, reduce the amount of dust generated.

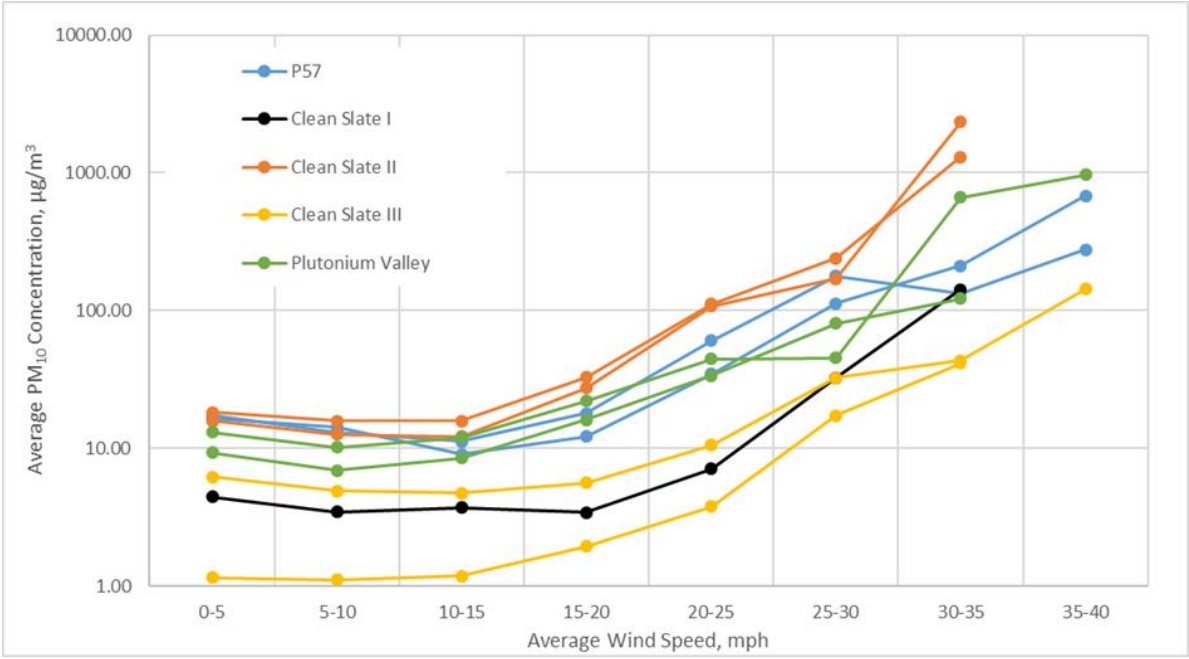

Figure 3. PM_{10} trends as a function of wind speed for the monitoring station at Clean Slate I and the two monitoring stations at each of the other sites (Clean Slates II and III, P57, and Plutonium Valley).

Over 85 percent of the sustained winds greater than 15 mph at the monitored Soils Activity sites are from the north, northwest, and south. Accordingly, many of the high dust events at these sites are associated with these wind directions. Although the detailed environment and contamination conditions differ from site to site, the Soils Activity sites have similar dust transport characteristics overall, consistent with their similar climates and physiographies (Appendix B). The critical effects of humidity, soil moisture, and wind parameters on dust transport at these sites highlights the importance of meteorological observations and allows these observations to be used to indicate possible dust movement and radionuclide transport.

High-wind events that generated the transport of radionuclide-contaminated dust were observed at both the Clean Slate sites and Project 57, where air filters were collected and analyzed. Although the air filters sampled two-week periods and an individual high-wind event generally has a duration of less than eight hours (recorded by the meteorological equipment at each station), the gross alpha concentrations for filters sampling during periods that included high-wind events were often larger than the concentrations for filters sampling during comparatively less windy periods. A comparison of samples collected upwind and downwind of a contamination area for a given wind event indicates a disproportionate increase in gross alpha compared with the increase in dust loading on the filters (i.e., the increase in gross alpha was not simply due to an increase in dust loading, but also to the source of the dust from the contamination area), indicating that radionuclides were suspended as the wind crossed the site. The high concentration spikes measured at Project 57 relative to the Clean Slate sites reflect the very-fine-grained and friable nature of the Project 57 site-specific soils and the differences in source concentration.

Alpha spectroscopy analyses were not performed for every filter, limiting the opportunities to correlate the analyses with wind conditions, but plutonium-239+240 ($^{239+240}$Pu) was detected in many of the air filter samples. Plutonium was also found in the near-ground passive traps at the Clean Slate and Project 57 monitoring stations. These findings indicate that $^{239+240}$Pu particles are transported by saltation during wind events, even from undisturbed surfaces. Analyses of specific wind events and the associated dust and radionuclide transmission can be found in Appendix C.

<u>When and how often do conditions associated with airborne radionuclide transport occur?</u>

There are seasonal and diurnal patterns in wind conditions that are common to the Soils Activity sites. Spring (March 1 to June 30) has the greatest frequency of winds exceeding 15 miles per hour (mph), which is often up to twice as frequent as other times of year. April and May are usually the windiest months (as shown in Appendices B and C). The lowest frequency of winds greater than 15 mph occurs in the fall (October 1 to November 30), with the frequency in summer (July 1 to September 30) and winter (December 1 to February 28) being slightly greater than in the fall. No overall seasonal increase due to monsoonal activity in the summer is observed. The diurnal pattern is characterized by a very low frequency of winds exceeding 15 mph during the nighttime hours. The daytime frequency is 3 to 10 times greater, with a significant increase during afternoon hours. During the spring at Plutonium Valley, winds exceeded 15 mph in the afternoon more than 20 percent of the time for three of the eight years of record.

The wind speeds of 15 mph and greater that prompt dust and radionuclide movement occur for relatively brief periods (approximately 7 percent to 12 percent of the year, depending on site), but they occur persistently year after year and will have a cumulative effect of moving radionuclides over time. If current climate conditions continue, this is equivalent to 7 to 12 years of winds in excess of 15 mph over a 100-year period. The effects of climate change on the wind speeds and frequencies at the sites are unknown, but projections of increased variability and greater extremes in precipitation patterns (see Appendix D) suggest that wind conditions will likely become more variable over time. These changes could also lead to an increase in the average speed. Because these winds will continue to transport radionuclides from the contamination areas and because radionuclides transported outside of those areas will continue to move downwind, contaminated soil will move farther from the sites. Given the predominant wind directions, the long-term effect will be to spread radionuclides to the south and north of the contamination areas.

Brief but exceptional whirlwind events known as dust devils also occur at the sites. Dust devils occur most frequently during hot, clear-sky conditions with light winds and they are caused by strong, uneven heating of the Earth's surface. The rotating column of air can loft dust hundreds of feet upward. Measurements at one of the monitoring stations at Project 57 suggest that the edge of a dust devil clipped the station on June 23, 2015 (Mizell *et al.*, 2017a). Wind direction shifted abruptly and repeatedly and was accompanied by increases in wind speeds from less than 10 mph to more than 30 mph in the course of a 20-second time span. Following this dramatic change in wind conditions, there was a gradual return to the prior observations. The air filter sampling during this event was found to have

radionuclide concentrations well above background. The whirlwind event was so brief that it could only be identified by reviewing data collected every three seconds. The averaged 10-minute data indicated no windstorms during the two-week sampling period.

What were the observed radionuclide concentrations associated with airborne transport?

The radionuclide concentrations discussed in this section are for air particulates collected on glass-fiber filters. By 2014, all of the Clean Slate and Project 57 monitoring stations used glass-fiber filters, but prior to that time, cellulose-fiber filters were also in use. Although gross alpha results for glass-fiber and cellulose-fiber filter samples overlap in their range of values, the radiological results for glass-fiber filter samples are statistically different from and greater than the radiological results for cellulose-fiber filter samples (Mizell and Shadel, 2016). The glass-fiber filters have a smaller pore size (0.3 µm), whereas the cellulose-fiber filters allow PM_{10} to pass through their 20 µm to 25 µm pores.

Gross alpha and alpha spectroscopy were determined to be the most effective analyses for quantifying air loadings of radionuclides at the Clean Slate and Project 57 sites. Gross alpha averaged 2.24×10^{-15} microCurie per milliliter (µCi/ml) for all of the monitoring stations adjacent to the Clean Slate sites during undisturbed conditions prior to remediation activities (Figure 4a) and 3.68×10^{-15} µCi/ml at the Project 57 stations (Figure 4b). These values are higher than the mean gross alpha concentrations measured at the Community Environmental Monitoring Program (CEMP) stations in the surrounding area, which typically ranged from 1 to 2×10^{-15} µCi/ml) (https://cemp.dri.edu/). The gross alpha concentrations of airborne material at the Clean Slate and Project 57 sites prior to the nuclear experiments are unknown, so the CEMP data are used to understand possible background conditions.

Periodic spikes in gross alpha concentration are observed at the sites and are attributed to airborne transport of radionuclides during wind events. The highest gross alpha measurement of 96.62×10^{-15} µCi/ml for a filter sampling at Project 57 Station 504 overlapped a wind event on March 30, 2017. This event registered wind gusts up to 50 mph from the north, so the high winds blew across the Project 57 contamination area before reaching Station 504. The effect of wind events is greater (resulting in higher radionuclide concentrations) at Project 57 than at TTR because of the very-fine-grained and friable nature of the soils at the Project 57 location and the higher radionuclide concentrations in the contamination area. An additional factor at all CAUs is proximity to the contamination source. Project 57 Station 504 was closer to the Project 57 ground zero high-contamination area than Station 503, and TTR Station 404 is closer to the Clean Slate II contamination area than Station 405 (as shown in the site maps in Appendix C). Both Station 504 and Station 404 also exhibit higher gross alpha concentration spikes than Station 503 and Station 405, respectively.

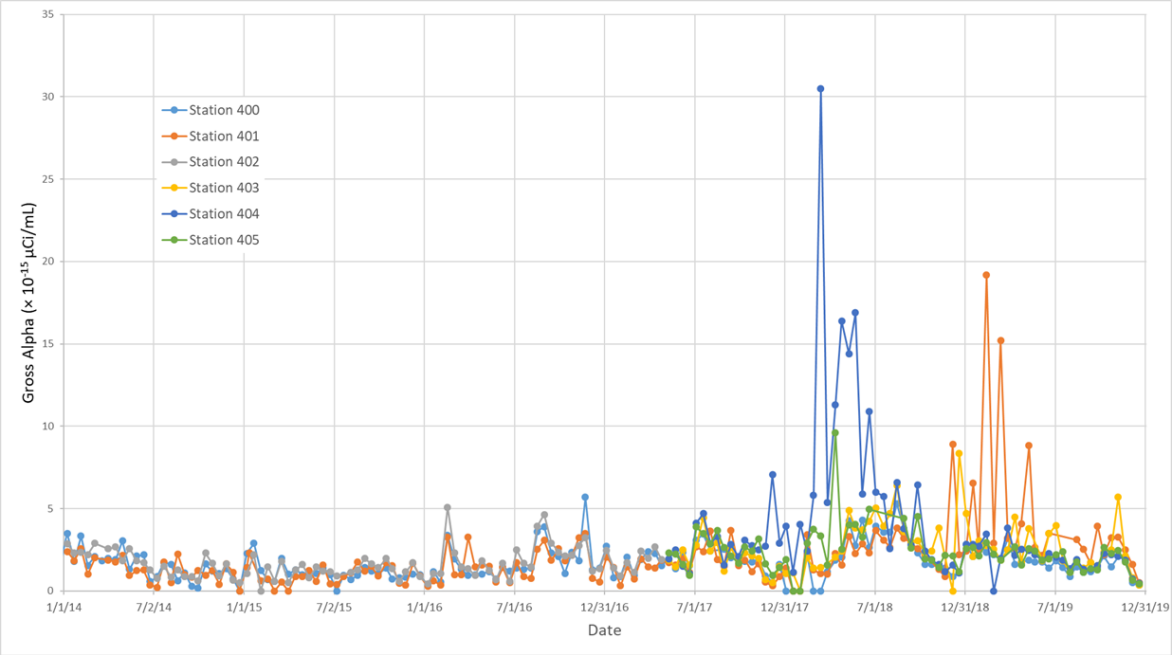

Figure 4a. Gross alpha measurements from air filters at the TTR Range Operation Center (Station 400) and Clean Slate sites collected from 2014, when glass filters were uniformly used, through 2019. Values reported below the measurement detection limit appear as zero in the graph. Remediation activities began in 2017.

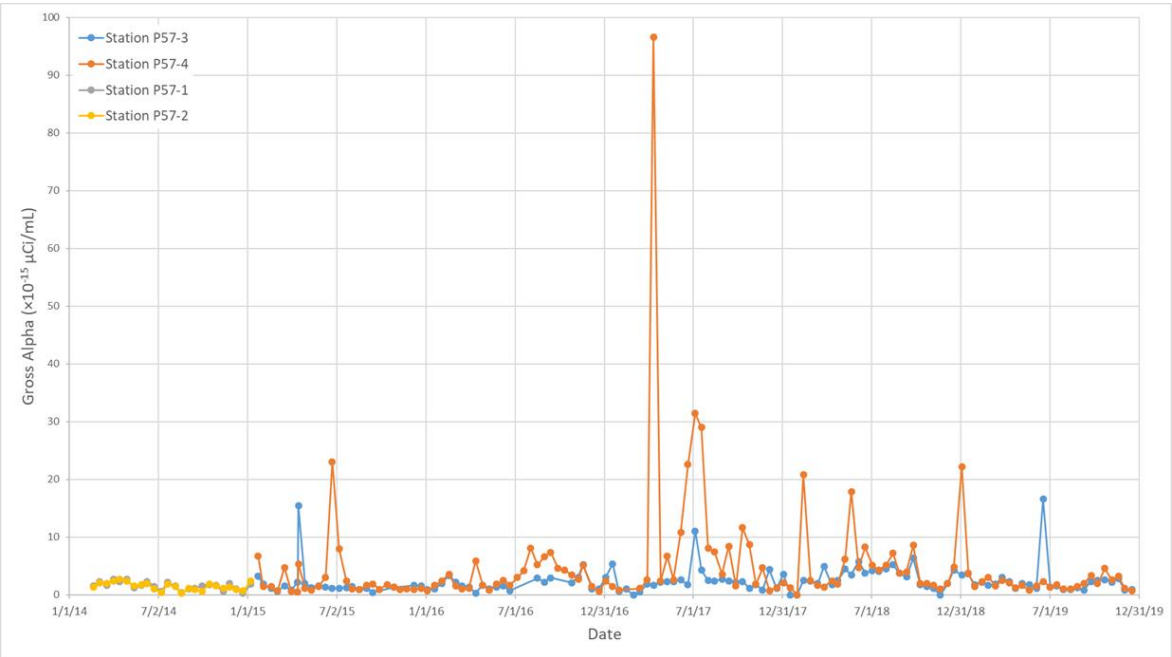

Figure 4b. Gross alpha measurements from air filters at Project 57 collected from 2014, when glass filters were routinely used, through 2019. Values reported below the measurement detection limit appear as zero in the graph.

The mean $^{239+240}$Pu concentrations measured by alpha spectroscopy on air filters collected at the Clean Slate sites during undisturbed conditions varied from 1.35×10^{-16} µCi/ml to 15.22×10^{-16} µCi/ml. The maximum $^{239+240}$Pu concentration measured at any of the Clean Slate monitoring stations during undisturbed conditions was 83.78×10^{-16} µCi/ml. Mean plutonium-238 (^{238}Pu) concentrations for undisturbed conditions at the Clean Slate sites ranged from not detected to 1.15×10^{-16} µCi/ml, with a maximum of 1.67×10^{-16} µCi/ml.

The mean $^{239+240}$Pu concentration measured on air filters during undisturbed conditions at Project 57 ranged from 11.12×10^{-16} µCi/ml to 57.25×10^{-16} µCi/ml, with a maximum observation of 339×10^{-16} µCi/ml. Gamma spectroscopy of the filter with the maximum observation also detected americium-241 (^{241}Am). The mean ^{238}Pu at Project 57 during undisturbed conditions ranged from 1.09×10^{-16} µCi/ml to 2.90×10^{-16} µCi/ml, with a maximum of 7.65×10^{-16} µCi/ml. All of the maximum plutonium values at Project 57, as well as the ^{241}Am detection of 71×10^{-16} µCi/ml, were measured on the air filter deployed during the dust devil event described in the previous section.

Material collected in passive saltation traps was analyzed to determine the radionuclide concentrations of particles moving by saltation along the ground surface. In general, the highest concentrations were associated with the particle size fraction smaller than 63 µm, and the lowest concentrations were found in the largest size fraction (> 250 µm). The association of higher radionuclide concentrations with the smaller particle size fraction was found to be statistically significant for channel sediments at the Smoky Site (Mizell *et al.*, 2017b). This association has also been documented by other researchers (Colton, 1999; Shinn *et al.*, 1993). Therefore, it is likely that this same association can be applied to saltating particles. At the Clean Slate monitoring stations, $^{239+240}$Pu concentrations for saltating material varied from 0.9 picocuries per gram (pCi/g) to 2,390 pCi/g. The Clean Slate range observed for ^{241}Am was less than the detection limit to 165 pCi/g and ^{238}Pu ranged from less than the detection limit to 37.3 pCi/g in the saltation samples. At the Project 57 monitoring stations, $^{239+240}$Pu concentrations for saltating material varied from 0.3 pCi/g to 884 pCi/g. The range observed for ^{241}Am in Project 57 saltation samples was less than the detection limit to 178 pCi/g and ^{238}Pu ranged from less than the detection limit to 15 pCi/g.

Land-surface disturbance causes increases in locally generated dust and increases in the concentration of radionuclides on the dust particles. Air quality was monitored adjacent to Clean Slates II and III during ground disturbance associated with remediation activities. Gross alpha concentrations increased by at least 10 percent at the Clean Slate II and III monitoring stations during remediation to over 150 percent for the stations closest to the ground disturbance. Concentrations of $^{239+240}$Pu measured on air filters during site remediation activities were 100 percent to over 1,000 percent higher than concentrations measured before remediation, with the largest increases observed at the monitoring stations closest to the work. The mean $^{239+240}$Pu concentrations measured at the Clean Slate sites during remediation activities varied from 28.03×10^{-16} µCi/ml to 155.30×10^{-16} µCi/ml, with a maximum concentration of 378.67×10^{-16} µCi/ml. The mean ^{238}Pu concentrations measured during remediation varied from 0.35×10^{-16} µCi/ml to 2.27×10^{-16} µCi/ml, with a maximum concentration of 2.64×10^{-16} µCi/ml. Time series graphs of radionuclide

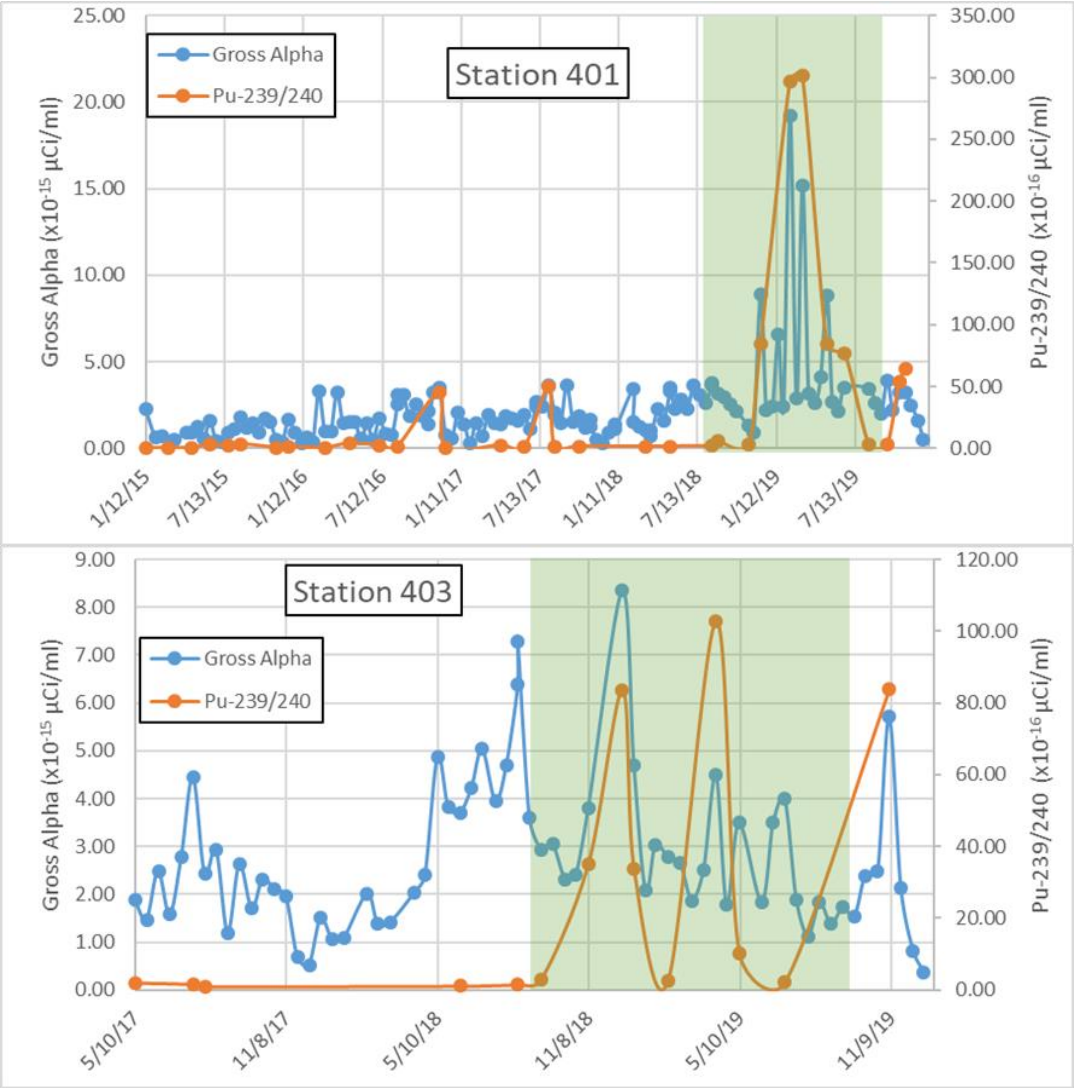

Figure 5. Gross alpha and $^{239+240}$Pu concentrations from air filters at monitoring stations adjacent to the Clean Slate III site. Station 401 has been in operation longer than Station 403. The time period of ground disturbance during remediation activities at Clean Slate III is highlighted in green.

concentration in suspended material demonstrate the effect of ground disturbance on air quality at the Clean Slate sites (Figures 5 and 6). If ground-disturbing activities occur at the Project 57 site in the future, it is expected that elevated radionuclide concentrations also will be present during that time frame and perhaps for some time after until the site restabilizes.

Gamma exposure rates measured with PICs at three of the TTR monitoring stations did not produce any identifiable contaminant migration results. Based on data collected from the TTR PICs and thermoluminescent dosimeters at Project 57, the annual gamma exposure rates at these sites are generally higher than the exposure rates in the nearby area monitored by the CEMP stations (https://cemp.dri.edu/cemp/). However, they are still approximately half of the national average exposure in the United States, which is 310 millirem from natural sources (NRC, 2011).

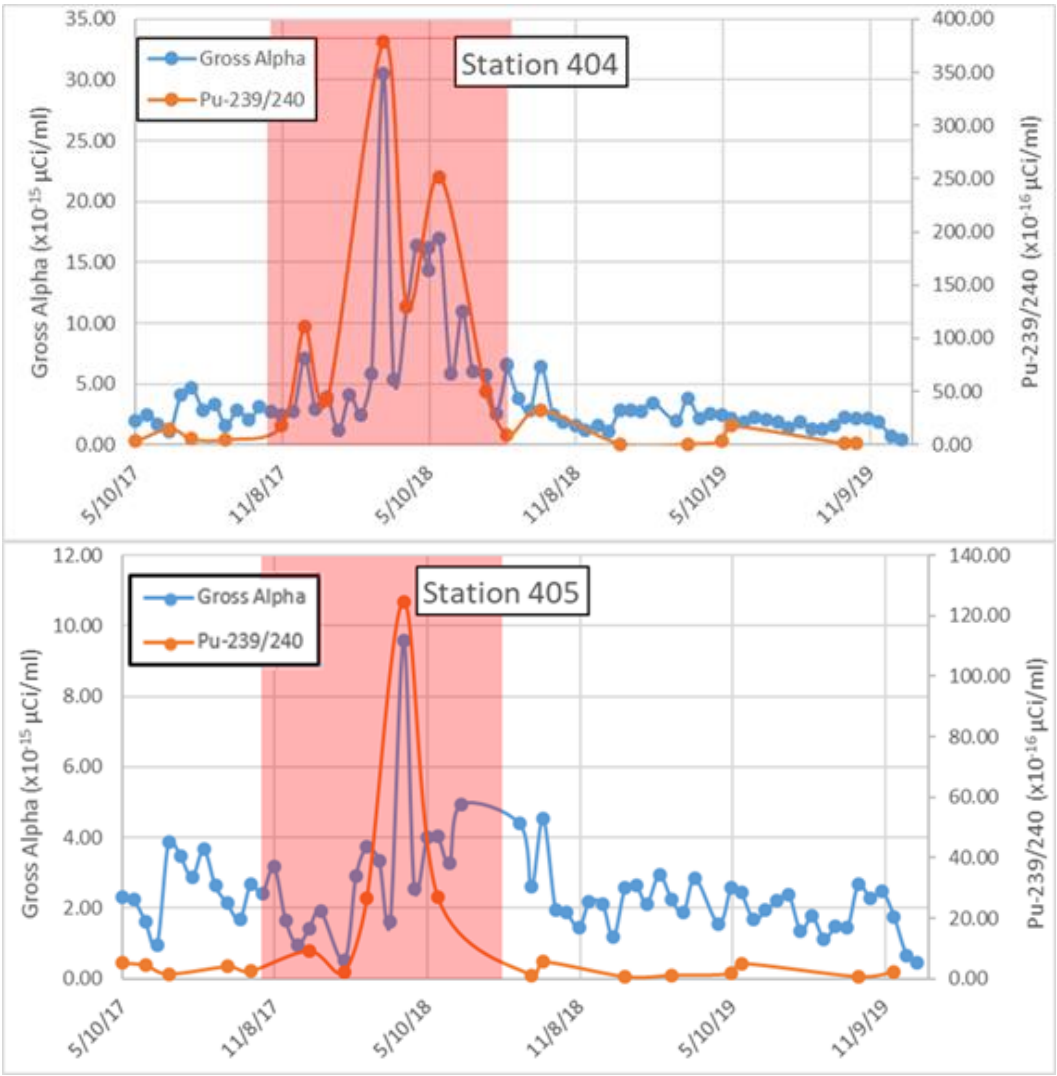

Figure 6. Gross alpha and $^{239+240}$Pu concentrations from air filters at monitoring stations adjacent to the Clean Slate II site. The time period of ground disturbance during remediation activities at Clean Slate II is highlighted in red

Waterborne Transport of Radionuclides

There are no perennial water courses at the CAUs. Therefore, movement of radionuclides by water at the Soils Activity sites is associated exclusively with runoff response from precipitation events. The climate at the Soils Activity sites is arid to semiarid. Precipitation records from gages on the NNSS, TTR, and NTTR show a bimodal pattern that is typical of the southwestern United States, with a peak in the winter months and a secondary smaller peak in late summer (Figure 7). During summer (May through September), precipitation is commonly the result of the North American monsoon weather pattern, which is characterized by short-duration, high-intensity, localized convective storms. In contrast, winter (October through April) precipitation events are usually associated with frontal storms with long-duration, low-intensity, regional precipitation. Generally, higher elevations receive more precipitation than lower areas in all months (Figure 7).

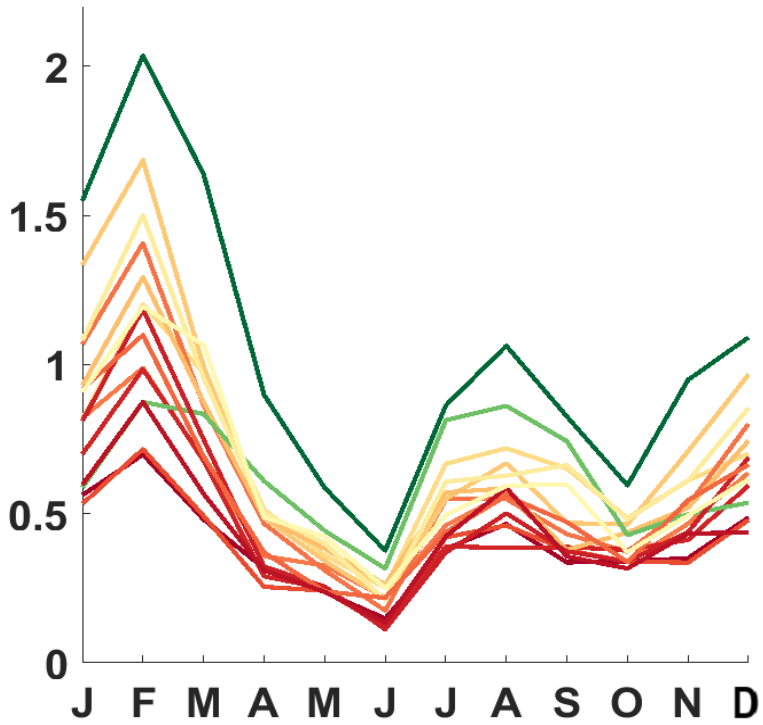

Figure 7. Average monthly precipitation at each National Oceanic and Atmospheric Administration rain gage on the NNSS. Each line represents one gage and the colors range from the lowest elevation gage (red) to the highest elevation gage (green). Gage locations are shown in Appendix D.

Evidence of waterborne contaminant migration has been observed at both the Smoky Site and Plutonium Valley. These observations prompted the instrumentation of channels passing through those sites. A summary of the combined findings from the Smoky Site and Plutonium Valley is presented below. In-depth presentation of radiological results from the instrumented channel at the Smoky Site can be found in Appendix E.

<u>How does the waterborne transport of radionuclides occur?</u>

Moving water entrains sediment and can transport it downstream until slowing velocity results in deposition. Coarser material moves along the channel bed as bedload transport and finer particles are suspended within the flow. These processes can move enormous amounts of material through perennial streams and rivers, and the amount of suspended sediment carried by a channel increases proportionally to discharge. In the arid environment of the Soils Activity sites, sediment transport by running water primarily occurs by ephemeral or episodic action during rainfall runoff in otherwise dry channels. Broad, unconfined, surface-water movement (e.g., sheetflood) is typically at a lower velocity than channel flow, and therefore it has less of an effect on erosion and sediment movement. During the monsoons, intense bursts of rain largely become runoff because the soil cannot absorb precipitation at the rate it is falling. During the rest of the year, runoff occurs because of “saturation excess,” which is when antecedent soil moisture fills the soil pore spaces and

they cannot absorb more water. This typically occurs during multiday, low-intensity storms associated with the passage of winter frontal systems. With sufficient flow velocity, the runoff from frontal systems can erode and entrain soil particles, but the most damaging floods in terms of erosion, deposition, and transport are the result of summer monsoonal events. Radionuclide contamination is most often associated with silt and fine-sand-sized particles. The movement of material of this sediment size by water occurs as flow velocities exceed 3.0 feet per second (fps) (Garcia [ed.], 2008).

What conditions cause the waterborne transport of radionuclides?

Three things must occur to initiate radionuclide movement by surface water. First, in an ephemeral system, there must be a precipitation event. Second, the intensity of precipitation, given changing antecedent soil moisture conditions, must be high enough to generate runoff. Lastly, the volume of discharge combined with the channel geometry must create flow velocities of 3 fps or higher to initiate sediment entrainment and movement.

Detailed analyses of streamflow frequencies at the NNSS, TTR, and NTTR are provided in Appendix D and summarized here. The precipitation threshold for runoff generation varies by season. The flow events capable of sediment transport are the result of high-intensity precipitation events during periods of relatively high soil moisture content (e.g., after a previous rainfall event). These high-intensity events primarily occur during the summer monsoonal period. Daily precipitation thresholds of 0.03 inches per day (in/day) and 0.9 in/day are defined as thresholds that usually (>50 percent of days) generate runoff greater than 0 fps and 3 fps, respectively. The long-duration, low-intensity rainfall events that are often observed in association with winter frontal storms also cause channel flow, but generally at velocities insufficient to cause erosion and transport sediment. A runoff threshold for this mechanism is more uncertain because of the importance of antecedent soil moisture conditions, but a daily precipitation threshold for runoff generation outside of the monsoon season is defined as 0.2 in/day, which is the daily precipitation amount above which runoff occurred 50 percent of the time (Appendix D; Stillman, 2019).

Rainfall intensity is the primary factor that controls runoff. Intense rainfall promotes runoff because the soil cannot absorb precipitation at the rate it is falling. At both the Smoky Site and Plutonium Valley, storms producing approximately 0.05 inch of precipitation during a 10-minute interval produced flow in the instrumented channels, although intensity at 0.1 inch in 10 minutes or higher was needed to consistently result in measurable flow. Rainfall exceeding an intensity threshold of 0.1 inch in 10 minutes was routinely observed during the summer at the Smoky Site and flow typically peaked approximately 30 minutes after the maximum 10-minute precipitation occurred. Precipitation intensity above that threshold was also observed at Plutonium Valley, but less frequently.

The transport of sand-sized and smaller particles of unconsolidated desert sediment typically begins when flow velocity exceeds a threshold of 3 fps to 4 fps. Greater velocities are capable of transporting larger and heavier material. This velocity threshold was exceeded multiple times during the course of monitoring at the Smoky Site and it was always the result of summer convective storms. A storm on August 1, 2015, is a typical example (Figure 8). The precipitation event peaked with a maximum intensity of 0.52 inch in 10 minutes and the peak water depth in the flume (26.63 inches) occurred 30 minutes after the peak

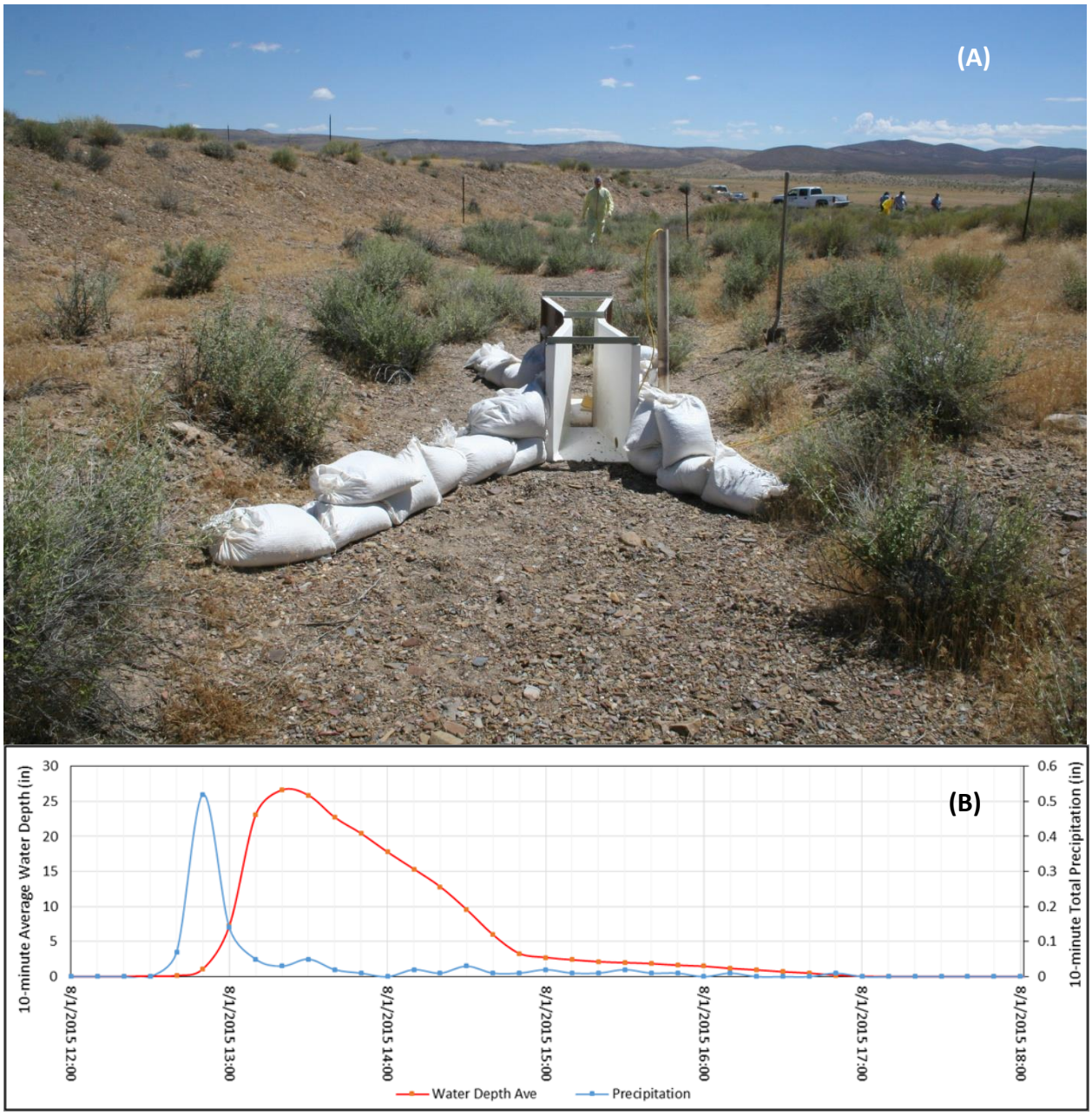

Figure 8. Example of a runoff event in the channel at the Smoky Site. A) View looking downstream through the flume in the Smoky Site channel and B) total precipitation and average water depth in the flume for 10-minute measurement periods for the precipitation and flume flow recorded on August 1, 2015. From Mizell *et al.* (2017c).

precipitation. The entire flow event lasted five hours and the peak water depth overtopped the flume. Based on the discharge (3.9 cubic feet per second [cfs]) associated with the maximum depth of flow (18.0 inches) for this flume, the discharge during the overtopping flow was estimated to be in the range of 6 cfs to 7 cfs (Mizell *et al.*, 2017c).

When and how often do conditions associated with waterborne radionuclide transport occur?

Runoff due to rainfall events occurred during every year of monitoring at the Smoky Site. Observations at the Smoky Site between 2011 and 2018 recorded streamflow 57 times, although streamflow in excess of 3 fps occurred only three times. Runoff was observed nine times at Plutonium Valley between 2011 and 2019. Appendix D provides an analysis of precipitation records and a climatologic evaluation.

Statistical analysis of the long-term records from the NNSS precipitation gage network was necessary to assess likely flow events between 1959 and the initiation of fluvial transport monitoring on the NNSS in 2011 (Stillman, 2019). This assessment confirmed that precipitation exceeding the threshold for runoff generation occurred more frequently during the monsoonal period from July to September than during the rest of the year combined. However, based on the precipitation thresholds identified to cause runoff during both monsoon and nonmonsoon seasons, it is estimated that runoff likely occurred 60 to 70 times per decade, and streamflow exceeding 3 fps likely occurred one to two times per decade between 1959 and 2011 at the NNSS. Future changes in streamflow were assessed using downscaled global climate models (Appendix D; Stillman, 2019). The results suggest a 10 percent increase in runoff events per decade and a 25 percent to 50 percent increase in streamflow exceeding 3 fps per decade by the end of the twenty-first century. From this, it is reasonable to expect that of the 66 to 77 runoff events forecast per decade, approximately 3 events will be sufficient to transport radionuclide-contaminated particles downstream.

Analysis of the records for the TTR area indicate that the threshold for runoff generation was exceeded approximately 55 to 65 times per decade and streamflow exceeding 3 fps likely occurred just over one time per decade between 1928 and 2017. Compared with the historical record, the climate models suggest a 15 percent increase in runoff events per decade and a 50 percent to 100 percent increase in streamflow events exceeding 3 fps per decade (Appendix D). Precipitation records are too limited at the Project 57 meteorological stations for meaningful analysis and no nearby proxy rain gages exist.

What were the observed radionuclide concentrations associated with waterborne transport?

Erosion and movement of contaminated material through numerous washes at both the Smoky Site and Plutonium Valley sites were noted during surveys supporting the demarcation of hazardous areas (Bechtel Nevada, 2000). Aerial surveys identified radionuclide-contaminated sediment along ephemeral channels at Plutonium Valley and found that ^{241}Am had moved 2,100 ft along one streambed and 1,700 ft along another (Colton, 1999). Trinity glass from atmospheric test locations (e.g., the Atmospheric Test Site T1) has also been noted to erode down washes and onto roads (Bechtel Nevada, 2000).

Sediment sampling was conducted in the channel monitored at the Smoky Site after flow events in 2013, 2014, and 2018, which had flow velocities in the channel large enough to move sediment. Samples collected from the channel bed downstream of the flume after these events all contained ^{241}Am, ^{238}Pu, and $^{239+240}$Pu, with the highest concentrations found on smaller particles. The average concentration for particle sizes less than 63 µm varied from 1.41 pCi/g to 11.46 pCi/g for ^{241}Am, 0.31 pCi/g to 2.33 pCi/g for ^{238}Pu, and 10.8 pCi/g to 60.72 pCi/g for $^{239+240}$Pu. The maximum concentrations measured were 57.5 pCi/g for ^{241}Am, 5.98 pCi/g for ^{238}Pu, and 351 pCi/g for $^{239+240}$Pu, which were all measured in samples

collected in 2018. There is a trend of increasing radionuclide concentrations in the channel bed samples over time. Appendix E presents the details of radiological activity over time in the Smoky Site monitored ephemeral channel.

The channel traversing the southernmost CAS at Plutonium Valley, which was observed to contain contaminated soil (Shinn *et al.*, 1993), was instrumented with a sampler to collect suspended sediment during significant runoff events. Sampling was triggered if both an adjacent photoacoustic distance sensor suspended above the channel and a pressure transducer installed in the channel bed indicated a depth of flow of approximately two to three inches. During the eight years of monitoring, flow was recorded in the channel nine times, but not at a depth sufficient to trigger suspended sediment sample collection. Bedload material collected in net traps installed in the thalweg (which is the line of lowest elevation) of the channel from 2011 to 2014 detected ^{241}Am, ^{238}Pu, and $^{239+240}$Pu, with generally higher concentrations on smaller soil particles. The average concentration for particle sizes less than 63 µm was 48 pCi/g for ^{241}Am, 5 pCi/g for ^{238}Pu, and 219 pCi/g for $^{239+240}$Pu. The maximum concentrations measured were 63.7 pCi/g for ^{241}Am, 7.3 pCi/g for ^{238}Pu, and 436 pCi/g for $^{239+240}$Pu.

Effects of Wildfire on Radionuclide Transport

Larger and more frequent wildfires are occurring in the western United States as a result of changes to a warmer and drier climate, and changes in ecosystem structure and composition (such as increased fuel loads caused by invasive annual grasses and past land-use practices). Historical return intervals of more than 100 years for large fires in southwestern deserts have been replaced by return intervals of decades (Clifford *et al.*, 2018). The Soils Activity sites addressed by EM NV through the NV FFACO variously occur in all three ecoregions on the NNSS: the Great Basin Desert, the Mojave Desert, and the transition ecoregion between the Great Basin and Mojave Deserts (Figure 1). The monitored TTR Clean Slate sites and Project 57 are within the Great Basin Desert, whereas the Smoky Site and Plutonium Valley are in the transition ecoregion.

Plant mounds are common features in these arid and semiarid ecoregions. A mound of accumulated sand and silt forms at the base of many shrubs as vegetation intercepts wind-borne particles. Smaller vegetation can grow out of the mounds and they are sites of biological activity for various fauna, which can augment the mound size. The measured levels of plutonium activity in contamination areas are higher in the plant mounds than in contiguous sparsely vegetated or bare soil areas (Friesen, 1992). When wildfire destroys the shrub anchoring a plant mound, wind can then erode the accumulated fine soil of the plant mound, which leads to resuspension of the associated radionuclides. Erosion by runoff can also lead to the transport of the radionuclides accumulated in fine material in the mounds after the shrub is killed.

<u>When elevated emissions are measured following a fire event, do those emissions originate from the soil mineral constituents or from burned plant material?</u>

The chemistry of particulates collected on air filters indicates that burned plant material is a contributor within the first month after the burn, but the long-term increase in dust emissions observed at the Great Basin Desert fire site was almost exclusively due to soil mineral particles. Because the Great Basin Desert fire was a prescribed burn, the pre-fire

measurements taken facilitated detailed pre- and post-burn comparisons, revealing the breakdown of soil structure caused by the fire. The soil structure deteriorated from a strong, definable pre-burn structure to a weakly cohesive, massively unstructured surface soil immediately after the burn (Figure 9). Soils in the transition ecoregion fire had largely returned to pre-fire conditions after two years.

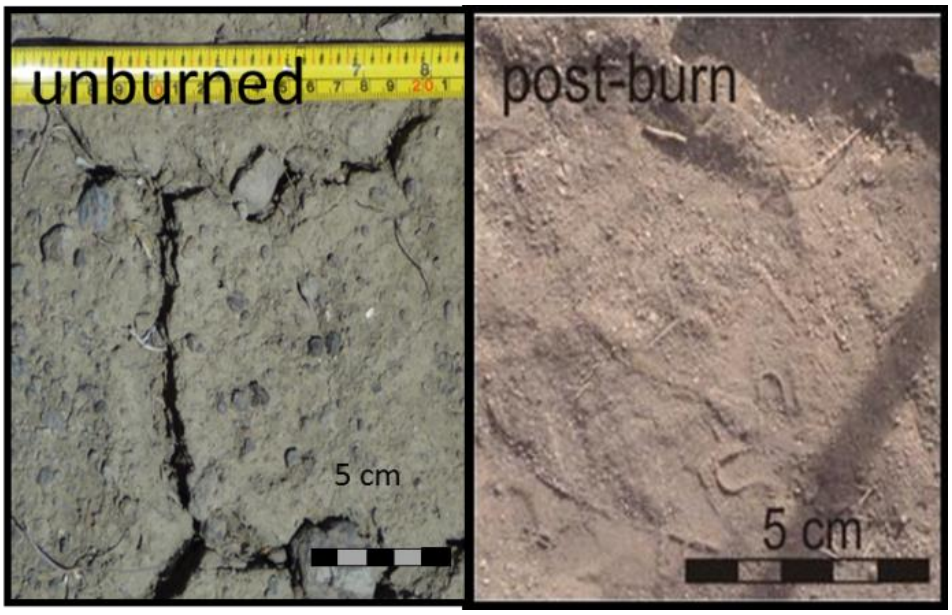

Figure 9. Unburned soil (left) at the Gleason Fire site showing a cohesive surface and the blocky soil structure of a well-developed soil compared with the burned soil (right) that shows a noncohesive dusty surface that lacks the blocky soil structure previously present.

Is there increased wind erodibility post-fire and if so, how long does it persist?

The greatest post-fire wind-erosion risk is associated with the Great Basin Desert ecoregion, where landscapes and ecoregions are higher in plant density and biomass. The Great Basin Desert fire study area (the Gleason Fire site) had substantially higher post-fire emissions than the other areas. Wind erodibility was substantially increased by the fire because of the exposure of large plant undercanopy areas previously protected from wind by now-burnt shrubs and trees, as well as changes in the overall aerodynamic roughness of the landscape caused by the burning of large numbers of plants and trees.

A lower risk of increased post-fire wind erosion is associated with the Mojave Desert ecoregion, although invasive grasses are increasing fire frequency and density. The loss of vegetation because of fire has less effect on the Mojave Desert ecoregion because there is less vegetative plant cover even under pre-fire conditions. The White Rock Fire site in the Mojave Desert was the least affected by fire in terms of wind erodibility, compared with the Great Basin Desert and transition ecoregions, though being an older fire site, some surface stability is expected.

Enhanced wind erosion remained at the Great Basin Desert fire site throughout the three-year study. By two years after the burn in the transition ecoregion, the PM_{10} emissions from burned interspaces and plant undercanopies were not greatly different from emissions from unburned areas. The Mojave Desert site also showed no enhanced emissions from burned areas two years after the fire (and possibly earlier because the post-fire measurements did not begin until two years after the fire), although comparing the areas burned two years ago with surfaces burned 25 years ago indicated that PM_{10} emissions had decreased over those two decades. In addition to the effects of the fire, many environmental parameters and conditions have profound effects on the landscape's potential for wind erosion, so considerable variability in recovery time is to be expected.

Is there increased runoff after a fire due to water repellency and if so, how long does it persist?

Overall, increases in runoff from the burned areas, regardless of ecoregion, do not persist for more than several years after a fire. Water repellency was evident for the Great Basin burned soils, with greater runoff observed on burned interspace soils (which are the intercanopy spaces between shrubs) than on unburned soils. In terms of runoff, the Great Basin soils were returning to pre-fire conditions at the end of three years after the burn. Runoff was not markedly different on burned and unburned surfaces for fire sites in the Mojave Desert and transition ecoregions.

How long does it take for vegetation to return to pre-burn levels?

Shrublands of the Great Basin and Mojave Desert and the transition ecoregion often require decades to return to vegetation states similar to unburned areas (Miller *et al.*, 2013). Vegetation recovery to pre-burn levels did not occur at the study sites during the three-year post-burn observational period and an old burn at the Mojave Desert site continued to have a different vegetation composition than unburned areas after 25 years. Revegetation of native perennial vegetation was observed at all the fire study sites, with the Great Basin Desert dominated by forbs and grasses and the transition ecoregion and Mojave Desert dominated by shrubs and forbs (the Jacob Fire transition ecoregion site was seeded by the U.S. Bureau of Land Management). Post-fire invasive species were observed at all of the fire-study sites, with cheatgrass being most common in the Great Basin Desert and transition ecoregion and red brome being more common in the Mojave Desert. These invasive annual grasses can increase subsequent fire potential and fire severity by adding fuel and increasing fuel connectivity.

Soil Stabilization Technology

Technologies for reducing erosion also have the potential to reduce the movement of radionuclides from the Soils Activity CAUs by wind and water. Some techniques for controlling erosion have been used for millennia and others continue to be developed. The analysis of soil stabilization approaches summarized here was published in 2014 (Shillito and Fenstermaker, 2014) and it reflects the techniques and approaches used up to that date.

What are the most effective stabilization techniques for the Soils Activity CAUs?

Effective soil stabilization is site and condition specific and should be assessed individually for each situation. Overall, mechanical stabilization methods are likely to be most applicable for controlling waterborne movement of radionuclides by precipitation runoff. In existing channelized flow situations at the Smoky Site and Plutonium Valley, geotextile and mulch applications and barriers such as riprap, mats, and slope/flow control hydraulic structures could be used to control erosion and bedload movement. If enhanced runoff across possible hydrophobic surfaces denuded by fire is the concern, mulching can be effective to reduce splash erosion and runoff and promote revegetation. Descriptions and references regarding these techniques can be found in Shillito and Fenstermaker (2014).

Adding physiochemical stabilizers to the soil can help control airborne contaminant transport by controlling dust suspension and saltation. These range from cement and clays to organic and polymer products that can be added to strengthen and stabilize the soil, as well as increase infiltration and moisture retention. Other techniques for reducing wind erosion rely on increasing the surface roughness to reduce the wind shear that reaches the erodible soil surface. Examples include staggered arrays of straw bales, gravel, or manufactured roughness elements.

Several methods of soil stabilization have been used at and near the NNSS, including capping, burying, recontouring the surface, adding polyacrylamide and other proprietary emulsions to soils, and adding mulches. These methods were used in combination with revegetation.

How long are stabilization treatments effective?

Long-term soil stability may be achieved by revegetating disturbed, eroding landscapes. Reestablishing the vegetation density and species richness to predisturbance levels will reduce water erosion by intercepting raindrops before they strike the soil, which will increase water infiltration into the soil and reduce runoff velocity (Sotir and Gray, 1989; Goldsmith and Bestmann, 1992). Vegetation increases surface roughness, which reduces wind velocity near the soil surface and supports microbial communities that increase soil cohesion and infiltration, all of which reduce wind erosion and airborne dust suspension and saltation.

In arid regions, revegetation is a slow process that requires years to develop and often multiple seasons of irrigation. In the Great Basin region, seeding accompanied by mulching prior to winter precipitation was found to be adequate, whereas supplemental irrigation is needed for successful germination and growth in the drier transition and Mojave Desert ecoregions (Anderson and Ostler, 2002). Plastic mulches resulted in more germination and better plant establishment rates than straw mulches (Anderson and Ostler, 2002). Stabilization of soils and control of herbivores (such as horses, rabbits, and ants) will also increase success rates.

Maintenance of soil stabilization activities is necessary for continued erosion control. Physiochemical stabilizers added to soil can lose effectiveness within one to three years of application. Most mechanical stabilization methods also require maintenance, such as the reapplication of mulch or reinstallation of wind barriers. In short, without ongoing

maintenance, the effectiveness of stabilization methods can be expected to diminish if not outright fail within several years. Therefore, they are best considered for situations in which a short-term reduction in the erosion rate meets a site management goal. For example, engineered stabilization can be used to control erosion accelerated by wildfire or land-disturbance activities until revegetation has succeeded in returning the landscape to a more stable erosion condition.

LONG-TERM SITE MANAGEMENT AND MONITORING

The Smoky Site, Plutonium Valley, Clean Slate and Project 57 CAUs have all been closed in accordance with the NV FFACO. The Clean Slate sites are designated as clean closures, whereas Smoky, Plutonium Valley and Project 57 were closed with a combination of no further action and closure in place with use restrictions. Therefore, minimal actions are required by regulatory agreement, and are limited to activities such as posting warning signs for any use restrictions, and inspecting to ensure the signs are in place, intact, and legible. Nonetheless, the research reported above can be used by land managers for stewardship decisions, planning long-term oversight during routine conditions, and developing response plans for specific events such as wildfires.

Implications of Site Research for Long-term Management

All of the Soils Activity sites discussed above, and many others on the NNSS, have been closed with mobile, long-lived radionuclides remaining in place. The term “clean closure” as applied to some of these sites does not mean the absence of contaminants of concern, but rather the risk-based closure recognizes that the combination of contaminant concentration and likely exposure time result in minimal radiological risk to human health. The studies of conditions for contaminant migration summarized above can be used to guide the management of Soils Activity sites to maintain personnel exposure to radionuclides at levels as low as reasonably achievable (ALARA). Management approaches to promote ALARA personnel exposure at these closed Soils Activity sites include the following:

- Worker and visitor presence should be minimized on sites whenever winds are in excess of 15 mph. The 15 mph threshold is the speed above which dust concentrations are observed to increase. Dust sourced from these sites often has radionuclide concentrations above background, even when there is no disturbance activity, with higher concentrations associated with the finer particle sizes people can inhale.
- Preplanned on-site activities should be avoided in spring, particularly April and May, because winds greater than 15 mph are historically most common during these months. Similarly, preplanned activities should be avoided during the usual period of the North American monsoon (July and August), when very high winds can onset rapidly and relative humidity and soil are dry.
- If on-site and near-site activities can occur anytime during a 24-hour period (for example, military training), nocturnal and early morning scheduling would increase the likelihood of wind speeds less than 15 mph because winds are consistently lower at night and until approximately 9:00 am. The greatest likelihood of high winds occurs in the afternoon, so avoiding afternoon site activities reduces the chance of encountering high winds.

- After precipitation events near and above a threshold of 0.1 inch per 10 minutes, activities in channels downstream of contamination areas should be suspended until radiological surveys can be performed to confirm conditions. Precipitation intensity above 0.1 inch per 10 minutes is associated with sustained runoff and transport of contaminants in suspension and bedload. In particular, contaminant migration both across Circle Road in a channel downstream of the Smoky Site and downstream of the detention basin in Plutonium Valley have been observed.
- Runoff control hydraulic structures, such as the detention basin at Plutonium Valley, require infrequent but important maintenance. If a sedimentation basin is constructed within the Smoky Site CAU to prevent radionuclide transport across Circle Road, it will also require periodic maintenance. The Plutonium Valley detention basin is filling with sediment, which will reduce basin capacity and lead to overflow around the edge of the spillway. This allows runoff and any associated radionuclide-contaminated sediment to enter the natural channel downstream that discharges into Yucca Lake. Routine maintenance includes removing sediments (and contaminants) from the basin to maintain design volume and repairing overflow erosional features that have established around the edges of the spillway. Vegetation and other debris that decrease basin capacity should also be removed.

The presence of long-lived radionuclides at the closed Soils Activity sites and the ability of the contaminants to migrate are likely to periodically raise questions on the part of some stakeholders regarding whether contaminants have migrated to areas with more human activity. Such questions could lead to calls for additional assessment and/or remediation. Although the existing NV FFACO closure documents provide excellent records of the site investigations and bases for decision-making, they may not be the most effective communication tools. Management can facilitate interactions with future stakeholders by the following:

- Communication plans regarding the presence of radionuclides at the sites can be developed. Such plans would explain the known and anticipated distribution and migration behavior of radionuclides, as well as why radionuclide detections outside contaminant boundaries do not indicate a failure of the site closure. The plans can be used to clearly identify what on-site activities are allowed and not allowed and convey recommendations that promote ALARA principles.

Implications of Site Research for Monitoring

The NV FFACO closures of the Soils Activity sites require minimal maintenance and monitoring, and no further action is needed in many cases. Nonetheless, the ongoing presence of long-lived radionuclides on the land surface raises the possibility that it may be in the land manager's best interest to maintain some level of monitoring activity or preparedness. For example, although decades have passed since nuclear tests occurred on the NNSS, public interest remains in the potential effects of these tests. Based on DRI's experience with the nuclear tests conducted off the NNSS, attention may resurge at the closed Soils Activity sites for a variety of reasons, such as the occurrence of some natural phenomenon near the site, emergence of health concerns or clusters for a population with associations to the site, publication of monitoring data by an independent group, or simply media attention to a "forgotten" nuclear activity or site that generates interest. It is always

preferable for the land manager to have data on hand or be able to readily collect it. To that end, considerations for monitoring are presented below, all of which would occur outside the context of the NV FFACO closures. Considerations related to monitoring the physical environment are as follows:

- Conduct event-based monitoring of bedload material after runoff-inducing precipitation events (i.e., those with precipitation intensity of 0.1 inch per 10 minutes). The purpose would be to maintain awareness of radionuclide migration downstream in drainages so that ALARA-based actions can be taken if indicated by the results.
    - Monitor the magnitude and the intensity of rainfall at the Smoky Site, Plutonium Valley, and other Soils Activity sites with established drainages through contamination areas (e.g., Clean Slate II) to provide the environmental data needed for event-based monitoring.
- Monitor concentrations of radionuclides in soils collected in the predominant downwind direction(s) outside of the contamination areas. Periodically assessing radionuclide concentrations in soil is a less labor- and equipment-intensive monitoring process than air monitoring. It is also appropriate for the long-term and incremental nature of wind-driven soil particle movement. The tests conducted at these sites dispersed contaminants beyond the designated contamination areas, so it will be important to have comparable measurements of current conditions to evaluate changes. The monitoring frequency can be low (with multiple years between measurements). The data would be useful for assessing land-use plans adjacent to the sites and responding to concerns raised by people conducting activities adjacent to the sites. Drone-based radiological surveys may be an efficient method of monitoring.
- Implement event-based monitoring of air quality during site disturbances and after wildfires. The air monitoring conducted during remediation activities at Clean Slate II and III documented the significant increase of airborne radionuclide contamination caused by disturbing the land surface. The fire studies demonstrated that for the Great Basin Desert ecoregion, where the TTR sites and Project 57 are located, fires increase wind erodibility for more than three years after a fire. Post-fire particulate emissions were predominantly fine soil particles (which are statistically associated with higher radionuclide concentrations than larger particle sizes) rather than burned plant material. Disturbances of the surfaces of the closed sites may generate concerns that can be addressed by air monitoring.
    - Event-based monitoring should focus on air-quality monitoring by collecting filters and conducting gross alpha and alpha spectroscopy analyses, as well as collecting meteorological data pertaining to wind speed, wind direction, precipitation, and relative humidity. Gross alpha and alpha spectroscopy are the most useful analytes for monitoring radionuclide concentrations at the sites. Gross beta, gamma spectroscopy, and gamma exposure rate data are less effective analytes for monitoring migration. Glass-fiber filters are recommended for air sampling because they have a smaller pore size than cellulose-fiber filters.

Given the risk-based criteria used, the Soils Activity site closures depend on assumptions of exposure by people to the on-site contaminants. The closure decisions state that a change in land use will require reevaluation of the closure conditions, but no process for recognizing such a change is required. The durability of the risk-based closure process can be improved through the following:

- Monitoring personnel activities to verify exposure scenario assumptions. The NNSS Real Estate/Operations Permit process (REOP) and other work control processes may provide one way of documenting activities (or lack thereof) at a site. Sites with access gates could be fitted with counters to monitor access.
- Monitoring human activities within a perimeter around a site to identify any differences between on-site exposure and near-site exposure. It is reasonable to forecast that contaminant concentrations encountered outside a site boundary as a result of radionuclide movement by air and water will be lower in response to dispersion than those measured within a site. However, the concentrations determined to be acceptable during site closure depend on the exposure duration assumed. The exposure assumptions range from 80 hours per year (hr/yr) to 2,000 hr/yr for the Soils Activity sites evaluated here. If the exposure time is markedly greater for a location where radionuclides are moving compared with the exposure time assumed within a site boundary, it is conceivable that a person could receive a higher dose than prescribed by the closure decision. Presumably, this possibility was one motivation for the Best Management Practice use restrictions established around the Smoky Site and Plutonium Valley CAUs. Knowledge of the general exposure durations for people proximal to the sites would be useful information for site managers in the event exposure concerns arise in the future.
- Documenting the effectiveness of institutional control processes in preventing inadvertent exposure at a select location or locations. This would provide data to substantiate relying on these processes for site control. Lessons learned from instances in which institutional control processes broke down should be documented, including root cause analysis, and shared among land managers and site stewards for other Soils Activity sites.

Responses to Potentially Adverse Events

Events that may enhance radionuclide movement from closed Soils Activity sites include the natural processes of extreme wind and rainfall events, as well as changes in erosion characteristics due to geomorphic or tectonic landform changes. Human-induced processes of ground disturbance can also increase radionuclide movement. Wildfire may result from either natural or human-induced causes.

The previous section describes considerations for event-based monitoring after major runoff events and site disturbances. Because of the unpredictability and often short duration of extreme wind events (e.g., dust devils), wind event-based monitoring is not practical without implementing continuous air monitoring.

Monitoring or site inspection may indicate that mitigation actions should be considered after a potentially adverse runoff event. If flooding creates new channel geometry and/or carries bedload and suspended radioactive material into areas of possible human exposure, possible response actions include the following:

- Design and construction of hydraulic structures to direct runoff to preferred areas and control the deposition of suspended and bedload material.
- Modification of control area boundaries.
- Removal of "hot spot" material beyond existing control area boundaries.

Response actions that may promote restabilization after ground disturbance and wildfire at Soils Activity sites include the following:

- Application of physicochemical stabilizers and/or mulch to reduce wind-borne erosion for the first several years. Although these actions are not long-term solutions, they may help until revegetation or other mitigative conditions can be emplaced.
- Revegetation of the disturbed area using enhancement techniques such as irrigation, mulching, herbivore exclosures, and windbreaks as needed.

CONCLUSIONS

The closed Soils Activity CAUs have long-lived radionuclides on the land surface at concentrations determined not to be harmful to human health under exposure scenarios approved in the risk-based closure process. These radionuclides are chemically bound to soil particles and these soil particles move by both airborne and waterborne processes. Therefore, contaminated soil has been and will continue to be transported beyond administrative and physical boundaries.

The environmental conditions supporting radionuclide movement at the Soils Activity sites include wind speeds in excess of 15 mph and rainfall intensity greater than 0.1 inch in 10 minutes. These events occur infrequently but with consistent seasonal predictability at the sites. Long-term monitoring identified the movement of radionuclides by suspension and saltation in response to wind and by suspension and bedload in channel flow. Contaminant concentrations in air were up to two orders of magnitude greater when strong winds moved across areas disturbed during remediation activities.

The use of administrative controls can reduce worker exposure to radionuclides and promote ALARA principles. On-site work should be avoided when wind speeds are 15 mph and higher. When scheduling work in advance, avoiding the spring season and the afternoon time frame will increase the likelihood of lower wind speeds. Radiological surveys should be conducted in channels crossing Soils Activity sites and downstream locations after runoff events to determine if access restrictions require adjustment. Examples of such locations include the Smoky Site at Circle Road and the T-4 site at Pahute Mesa Highway. Using soil stabilization techniques after ground disturbances or wildfires can reduce erosion and radionuclide movement while promoting revegetation to control erosion in the long term.

Although not required by the NV FFACO closure agreements, monitoring radionuclide concentrations outside the CAU boundaries would provide land stewards with data in the event concerns arise in the future on the part of stakeholders. The monitoring

programs conducted by EM NV to evaluate the processes of radionuclide migration from the Soils Activity sites were equipment intensive and required skilled personnel to maintain. Post-closure surveillance monitoring can be effectively performed primarily in an event-based mode after runoff or land-disturbance events in conjunction with routine but infrequent soil sampling downwind. These activities would allow land managers to maintain awareness of the effects of the closed CAUs on surrounding land areas, foster ALARA management practices, and respond with up-to-date and reliable data in the event of stakeholder concerns. Communication plans for each site would be helpful to document the radionuclides left in place, explain the risk-based closure decisions, and foster stakeholder understanding.

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APPENDIX B. LONG-TERM MONTHLY STATISTICS FROM EACH MONITORING STATION

Prepared by Austin Chapman

Table B-1. Station 400 long-term monthly statistics at Range Operation Center (ROC).

	Start Date: 6/1/2008; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	5.93	7.23	7.97	8.55	8.00	7.65	7.25	7.09	6.57	6.40	6.24	6.14	**AVG**	7.09
Wind Speed Max (mph)	36.39	33.42	34.64	35.77	32.15	33.95	37.5	30.53	30.78	37.28	31.48	32.09	**MAX**	37.5
Wind Speed Gust (mph)	51.95	49.32	51.95	54.65	46.54	49.98	62.18	46.69	48.37	54.36	47.93	46.91	**MAX**	62.18
Wind Freq from S*	27.11%	33.78%	42.83%	31.90%	34.08%	45.80%	63.44%	61.21%	49.73%	35.11%	35.63%	26.64%	**AVG**	40.60%
Wind Freq from NW**	50.73%	42.77%	37.60%	48.64%	45.00%	35.85%	13.15%	18.98%	29.98%	43.65%	40.15%	50.62%	**AVG**	38.09%
Air Temperature Avg (deg F)	34.23	36.54	44.12	50.89	58.48	71.42	76.75	74.79	66.74	53.16	41.44	31.90	**AVG**	53.37
Air Temperature Min (deg F)	-4.467	-8.373	3.38	18.77	27.9	34.48	48.2	44.08	28.64	13.71	5.954	-8.805	**MIN**	-8.81
Air Temperature Max (deg F)	69.49	74.7	76.28	84.02	90.1	101	101	99.59	94.42	86.31	78.26	65.53	**MAX**	101
Relative Humidity Avg (%)	59.91	55.24	44.31	35.09	33.13	20.62	26.93	24.71	28.25	36.04	45.39	59.81	**AVG**	39.12
Relative Humidity Min (%)	6.57	4.30	5.82	2.91	3.65	2.98	2.77	2.64	3.62	3.25	4.00	6.64	**MIN**	2.64
Relative Humidity Max (%)	100.00	100.00	100.00	100.00	100.00	96.30	98.60	99.40	100.00	100.00	100.00	100.00	**MAX**	100
Total Precipitation (inch)	2.35	3.50	5.56	4.24	5.89	1.42	8.72	3.52	4.11	3.77	2.43	2.84	**TOTAL**	48.35
Max Daily Precipitation (inch)	0.35	0.52	0.42	0.64	0.50	0.29	0.65	1.52	0.75	1.16	0.30	0.38	**MAX**	1.52
Soil Temperature Avg (deg F)	36.42	40.51	49.11	57.80	65.97	78.14	83.20	81.99	74.55	59.87	46.15	35.43	**AVG**	59.09
Soil Temperature Min (deg F)	5.85	10.20	7.09	17.71	34.67	34.53	51.55	44.34	33.74	18.51	12.38	-7.67	**MIN**	-7.67
Soil Temperature Max (deg F)	65.86	67.68	76.87	93.11	98.60	105.50	111.90	108.20	103.20	88.93	86.86	69.08	**MAX**	111.90

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-1. Station 400 long-term monthly statistics at ROC (continued).

	Start Date: 6/1/2008; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Soil Vol Water Content Avg	0.12	0.14	0.15	0.14	0.15	0.13	0.14	0.13	0.12	0.12	0.11	0.11	**AVG**	0.13
Soil Vol Water Content Min	0.06	0.07	0.07	0.01	0.10	0.09	0.08	0.06	0.02	0.05	0.05	0.05	**MIN**	0.01
Soil Vol Water Content Max	0.21	0.25	0.24	0.24	0.27	0.26	0.33	0.43	0.33	0.35	0.23	0.21	**MAX**	0.43
Solar Radiation Avg (ly/day)	127	183	249	317	352	399	363	341	283	212	147	113	**AVG**	257.17
Solar Radiation Max (ly/day)	181	255	331	406	435	452	439	411	351	280	204	151	**MAX**	452
Barometric P. Avg (in Hg)	24.63	24.54	24.54	24.51	24.50	24.54	24.62	24.61	24.59	24.60	24.61	24.58	**AVG**	24.57
Barometric P. Min (in Hg)	23.59	24.03	23.98	23.97	24.03	24.18	24.34	24.21	24.10	24.00	23.94	23.89	**MIN**	23.59
Barometric P. Max (in Hg)	25.08	24.99	24.94	24.90	24.94	24.84	24.85	24.81	24.88	25.02	25.01	25.02	**MAX**	25.08
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	1.32	1.79	2.66	2.68	2.35	2.79	2.82	7.14	1.89	1.98	1.55	1.43	**AVG**	2.53
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	222.90	45.00	558.10	91.50	57.40	365.00	47.60	164.30	81.80	116.30	81.90	258.94	**MAX**	558.10
PM_{10} Avg Concentration ($\mu g/m^3$)	5.24	6.74	11.42	8.23	7.46	10.98	9.52	18.71	7.52	7.62	5.88	5.16	**AVG**	8.71
PM_{10} Max Concentration ($\mu g/m^3$)	1,052.80	1,705.53	3,212.00	595.49	308.90	2,517.92	436.60	419.51	545.11	1032.50	386.30	1,155.92	**MAX**	3,212.00

Table B-2. Station 401 long-term monthly statistics at Clean Slate III.

	Start Date: 7/1/2008; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	5.65	7.26	8.12	9.05	8.34	7.74	7.20	6.79	6.27	6.18	5.82	5.97	**AVG**	7.03
Wind Speed Max (mph)	39.39	36.57	37.19	40.04	35.41	34.56	34.63	30.94	32.58	35.05	33.34	35.86	**MAX**	40.04
Wind Speed Gust (mph)	52.39	50.49	53.19	56.77	48.59	48.44	51.73	46.69	52.02	48.37	45.96	56.04	**MAX**	56.77
Wind Freq from S*	24.36%	33.43%	39.81%	29.39%	28.78%	42.88%	58.98%	62.80%	49.41%	37.88%	37.65%	25.32%	**AVG**	39.22%
Wind Freq from NW**	60.02%	49.73%	39.96%	52.10%	50.83%	36.89%	12.87%	10.78%	24.02%	41.84%	43.70%	57.79%	**AVG**	40.04%
Air Temperature Avg (deg F)	31.91	34.95	43.44	49.98	57.83	70.70	75.94	73.73	65.13	50.81	38.63	29.58	**AVG**	51.89
Air Temperature Min (deg F)	-12.68	-13.39	-0.53	10.63	21.59	26.06	39.21	36.83	25.12	-2.775	-2.361	-13.64	**MIN**	-13.64
Air Temperature Max (deg F)	69.01	77.38	82.02	85.6	93.67	106.2	105.1	102.6	98.71	88.12	78.17	64.62	**MAX**	106.2
Relative Humidity Avg (%)	62.73	58.43	48.04	37.64	35.15	22.21	29.02	27.10	31.18	39.05	48.07	61.76	**AVG**	41.70
Relative Humidity Min (%)	7.11	4.56	6.00	0.04	3.10	1.80	1.40	0.60	2.10	1.18	2.69	0.00	**MIN**	0.00
Relative Humidity Max (%)	100.00	100.00	100.00	100.00	100.00	98.40	99.70	99.20	100.00	100.00	100.00	100.00	**MAX**	100
Total Precipitation (inch)	2.26	2.37	3.93	2.70	6.26	0.54	8.78	4.27	4.99	4.38	2.09	1.91	**TOTAL**	44.48
Max Daily Precipitation (inch)	0.33	0.33	0.25	0.18	0.41	0.22	1.29	0.66	0.99	0.56	0.34	0.13	**MAX**	1.29
Soil Temperature Avg (deg F)	34.27	38.83	47.61	56.76	64.65	78.45	82.82	81.13	72.80	58.07	44.02	34.55	**AVG**	57.83
Soil Temperature Min (deg F)	9.95	10.11	23.78	30.02	31.65	41.87	51.33	49.26	29.99	4.89	12.61	9.16	**MIN**	4.89
Soil Temperature Max (deg F)	66.56	71.69	81.48	108.30	112.40	128.20	133.10	130.20	125.80	104.00	83.16	62.47	**MAX**	133.10
Soil Vol Water Content Avg	0.16	0.18	0.20	0.19	0.17	0.15	0.16	0.16	0.15	0.15	0.14	0.15	**AVG**	0.16
Soil Vol Water Content Min	0.10	0.11	0.13	0.12	0.12	0.10	0.10	0.09	0.08	0.08	0.07	0.07	**MIN**	0.07
Soil Vol Water Content Max	0.23	0.31	0.29	0.27	0.30	0.27	0.47	0.41	0.37	0.33	0.25	0.28	**MAX**	0.47

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).
**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-2. Station 401 long-term monthly statistics at Clean Slate III (continued).

	Start Date: 7/1/2008; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**AVG**	NA
Solar Radiation Max (ly/day)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**MAX**	NA
Barometric P. Avg (in Hg)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**AVG**	NA
Barometric P. Min (in Hg)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**MIN**	NA
Barometric P. Max (in Hg)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**MAX**	NA
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	1.50	1.78	2.04	3.81	2.21	2.45	2.86	3.95	3.08	2.51	2.25	1.20	**AVG**	2.47
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	909.24	316.71	152.80	639.70	178.10	595.12	88.60	180.90	235.49	393.88	545.62	127.40	**MAX**	909.24
PM_{10} Avg Concentration ($\mu g/m^3$)	10.23	6.50	8.05	10.06	4.74	10.04	9.51	11.52	11.19	12.48	9.27	4.64	**AVG**	9.02
PM_{10} Max Concentration ($\mu g/m^3$)	5,247.72	3,204.70	4,191.20	3,034.30	967.80	5,308.80	496.38	2,352.40	1,938.13	4534.72	2,391.11	3,679.50	**MAX**	5,308.79

NA = data not available.

Table B-3. Station 402 long-term monthly statistics at Clean Slate I.

	Start Date: 5/18/2011; End Date: 4/24/2017													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	5.32	6.41	7.24	8.56	8.07	7.49	7.10	6.59	5.92	5.63	5.29	5.85	**AVG**	6.62
Wind Speed Max (mph)	38.07	28.75	35.91	36.85	34.91	30.19	30.78	32.76	29.89	32.28	32.95	31.72	**MAX**	38.07
Wind Speed Gust (mph)	54.22	41.79	50.2	54.07	47.35	48.08	48.74	51.07	60.43	46.91	47.27	44.21	**MAX**	60.43
Wind Freq from S*	23.34%	29.04%	41.37%	30.77%	32.58%	49.72%	63.96%	65.33%	54.01%	39.62%	33.76%	20.17%	**AVG**	40.30%
Wind Freq from NW**	60.03%	54.83%	42.16%	54.74%	49.10%	31.62%	11.20%	9.96%	22.41%	43.42%	49.49%	65.07%	**AVG**	41.17%
Air Temperature Avg (deg F)	30.77	36.15	44.99	50.91	58.78	71.39	74.93	73.66	65.49	52.25	37.96	29.15	**AVG**	52.20
Air Temperature Min (deg F)	-12.56	-15.8	8.384	13.53	26.19	27.49	45.23	42.38	26.47	16.21	1.598	-7.797	**MIN**	-15.80
Air Temperature Max (deg F)	66.52	73.76	77.94	86.4	91.63	103.8	104.7	98.46	94.62	86.09	73.78	64.81	**MAX**	104.7
Relative Humidity Avg (%)	60.66	56.23	42.47	34.47	32.82	18.22	30.93	28.28	34.55	42.17	52.46	62.71	**AVG**	41.33
Relative Humidity Min (%)	4.44	1.04	1.94	0.00	1.67	0.01	0.02	0.24	1.88	3.06	4.97	7.90	**MIN**	0.00
Relative Humidity Max (%)	100.00	100.00	100.00	100.00	100.00	96.90	100.00	100.00	99.70	100.00	100.00	100.00	**MAX**	100
Total Precipitation (inch)	1.40	1.93	1.54	1.70	2.92	0.38	9.35	1.65	3.26	4.17	1.22	1.03	**TOTAL**	30.55
Max Daily Precipitation (inch)	0.18	0.36	0.34	0.41	0.75	0.12	2.53	0.53	1.38	1.13	0.33	0.29	**MAX**	2.53
Soil Temperature Avg (deg F)	31.96	37.79	47.01	56.40	65.65	79.00	80.62	79.97	70.47	55.17	41.09	32.13	**AVG**	56.44
Soil Temperature Min (deg F)	10.67	24.35	29.57	34.40	40.39	48.16	60.93	62.80	47.68	34.61	24.67	13.86	**MIN**	10.67
Soil Temperature Max (deg F)	47.05	53.46	66.92	82.33	89.58	101.40	102.00	99.91	92.12	74.26	58.57	49.37	**MAX**	102.00
Soil Vol Water Content Avg	0.10	0.12	0.12	0.12	0.11	0.09	0.11	0.11	0.09	0.11	0.10	0.09	**AVG**	0.11
Soil Vol Water Content Min	0.07	0.06	0.10	0.08	0.08	0.06	0.06	0.05	0.05	0.04	0.04	0.04	**MIN**	0.04
Soil Vol Water Content Max	0.17	0.20	0.21	0.19	0.19	0.15	0.35	0.24	0.29	0.28	0.22	0.14	**MAX**	0.35

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-3. Station 402 long-term monthly statistics at Clean Slate I (continued).

	Start Date: 5/18/2011; End Date: 4/24/2017													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	237	360	484	629	691	759	655	639	534	405	282	224	**AVG**	491.47
Solar Radiation Max (ly/day)	338	489	621	752	809	834	798	758	668	526	396	296	**MAX**	834
Barometric P. Avg (in Hg)	24.73	24.69	24.63	24.63	24.61	24.64	24.64	24.63	24.65	24.62	24.65	24.59	**AVG**	24.64
Barometric P. Min (in Hg)	23.34	19.26	22.90	23.51	24.15	24.39	22.37	22.53	22.65	22.68	23.05	22.35	**MIN**	19.26
Barometric P. Max (in Hg)	26.46	26.54	26.08	25.01	25.07	24.87	24.90	25.69	25.82	25.92	26.11	26.28	**MAX**	26.54
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	0.42	0.82	1.12	1.96	1.66	2.87	2.79	2.59	2.11	1.16	1.12	0.71	**AVG**	1.61
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	45.90	909.60	445.30	1,100.10	132.60	160.18	492.40	1,418.90	334.60	221.50	146.70	359.30	**MAX**	1,418.90
PM_{10} Avg Concentration ($\mu g/m^3$)	3.19	5.60	8.00	15.23	10.78	20.71	22.55	21.80	17.46	9.38	9.47	5.39	**AVG**	12.46
PM_{10} Max Concentration ($\mu g/m^3$)	694.24	1,719.10	1,296.30	3,999.50	2,073.23	970.70	1,685.40	6,062.68	1,864.17	1,111.50	618.83	1,482.00	**MAX**	6,062.68

Table B-4. Station 403 long-term monthly statistics at Clean Slate III.

	Start Date: 4/26/2017; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	4.91	7.66	7.12	8.11	7.51	7.20	6.35	5.76	6.15	5.56	4.72	5.00	**AVG**	6.34
Wind Speed Max (mph)	27.7	28.63	35.26	31.04	28.68	29.12	32.01	23.72	29.87	28.5	28.96	31.06	**MAX**	35.26
Wind Speed Gust (mph)	38.14	44.72	49.98	44.57	41.87	42.16	59.77	40.19	48.74	40.63	40.84	42.52	**MAX**	59.77
Wind Freq from S*	43.69%	43.06%	50.07%	24.10%	32.26%	39.11%	53.71%	54.77%	44.01%	18.94%	40.04%	20.56%	**AVG**	38.69%
Wind Freq from NW**	40.49%	44.41%	31.11%	49.25%	43.42%	38.90%	14.94%	12.80%	28.47%	56.28%	41.22%	55.86%	**AVG**	38.10%
Air Temperature Avg (deg F)	34.84	31.63	40.80	52.33	57.56	71.46	77.86	74.99	64.03	48.74	39.40	31.27	**AVG**	52.08
Air Temperature Min (deg F)	5.522	-8.535	-3.837	20.3	26.18	37.07	46.58	43.83	24.61	-4.215	-0.5259	1.094	**MIN**	-8.54
Air Temperature Max (deg F)	64.47	65.52	72.77	83.79	90.23	102.1	100.9	99.93	97.09	80.51	74.39	61.75	**MAX**	102.1
Relative Humidity Avg (%)	65.24	58.44	59.71	39.53	41.76	22.50	29.37	27.62	32.69	33.06	42.91	59.51	**AVG**	42.70
Relative Humidity Min (%)	9.53	6.37	9.49	3.40	4.92	1.88	2.95	3.71	3.18	1.02	2.71	8.35	**MIN**	1.02
Relative Humidity Max (%)	100.00	100.00	100.00	99.30	99.30	98.90	99.50	98.60	97.20	99.30	100.00	100.00	**MAX**	100
Total Precipitation (inch)	0.65	0.66	2.00	0.56	2.96	0.06	2.48	1.74	1.78	0.51	1.99	1.47	**TOTAL**	16.86
Max Daily Precipitation (inch)	0.21	0.31	0.42	0.19	0.51	0.06	0.52	0.61	0.65	0.27	0.77	0.40	**MAX**	0.77
Soil Temperature Avg (deg F)	35.15	34.61	43.83	59.02	65.74	81.98	86.40	82.90	70.10	53.56	42.14	32.56	**AVG**	57.33
Soil Temperature Min (deg F)	14.68	14.40	22.80	33.60	34.57	43.69	55.15	54.77	33.73	8.80	17.71	13.05	**MIN**	8.80
Soil Temperature Max (deg F)	56.50	63.54	76.86	97.65	109.50	127.30	125.90	118.70	114.90	92.32	76.64	56.21	**MAX**	127.30
Soil Vol Water Content Avg	0.16	0.19	0.23	0.23	0.22	0.20	0.18	0.21	0.19	0.17	0.16	0.16	**AVG**	0.19
Soil Vol Water Content Min	0.02	0.15	0.17	0.18	0.18	0.16	0.15	0.15	0.13	0.11	0.11	0.13	**MIN**	0.02
Soil Vol Water Content Max	0.19	0.24	0.30	0.29	0.31	0.28	0.24	0.31	0.32	0.27	0.21	0.21	**MAX**	0.32

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-4. Station 403 long-term monthly statistics at Clean Slate III (continued).

	Start Date: 4/26/2017; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	242	344	436	574	631	772	676	634	509	435	298	228	**AVG**	481.60
Solar Radiation Max (ly/day)	344	471	602	758	824	841	824	748	637	524	389	300	**MAX**	841
Barometric P. Avg (in Hg)	24.77	24.59	24.64	24.63	24.59	24.66	24.76	24.73	24.68	24.72	24.72	24.76	**AVG**	24.69
Barometric P. Min (in Hg)	24.32	24.16	24.20	24.31	24.25	24.29	24.52	24.51	24.21	24.36	24.10	24.37	**MIN**	24.1
Barometric P. Max (in Hg)	25.10	25.01	24.90	24.95	24.94	24.96	24.94	24.89	24.93	25.12	25.11	25.13	**MAX**	25.13
$PM_{2.5}$ Avg Concentration (µg/m^3)	0.18	0.30	0.67	2.45	1.09	1.50	1.34	1.34	0.95	0.76	0.69	0.57	**AVG**	0.99
$PM_{2.5}$ Max Concentration (µg/m^3)	11.99	10.87	29.29	992.91	45.64	873.58	38.70	37.14	55.39	206.69	555.40	926.30	**MAX**	992.91
PM_{10} Avg Concentration (µg/m^3)	0.92	1.44	2.71	13.15	5.36	10.78	8.88	7.62	6.32	4.29	4.62	4.46	**AVG**	5.88
PM_{10} Max Concentration (µg/m^3)	111.43	84.81	342.10	8,552.27	307.50	10,785.61	6,824.30	252.03	365.72	1,081.41	4,116.50	7,906.30	**MAX**	10,785.60

Table B-5. Station 404 long-term monthly statistics at Clean Slate II.

	Start Date: 4/26/2017; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	5.65	7.94	7.48	8.29	7.86	7.35	6.81	6.35	6.49	5.96	5.36	5.53	**AVG**	6.76
Wind Speed Max (mph)	28.97	29.62	34.57	30.05	28.75	28.11	28.21	24.78	25.23	29.52	28.89	32.34	**MAX**	34.57
Wind Speed Gust (mph)	41.14	43.04	49.1	44.72	44.42	42.09	43.47	41.57	40.33	39.82	40.04	45.3	**MAX**	49.1
Wind Freq from S*	35.25%	38.30%	46.18%	23.36%	30.47%	36.89%	47.49%	43.82%	37.51%	16.46%	31.02%	16.35%	**AVG**	33.59%
Wind Freq from NW**	32.12%	34.95%	24.18%	42.05%	36.84%	31.78%	10.38%	8.59%	21.06%	40.38%	27.91%	44.45%	**AVG**	29.56%
Air Temperature Avg (deg F)	34.60	30.99	39.90	51.11	56.36	70.02	76.57	73.96	63.16	48.44	39.81	31.43	**AVG**	51.36
Air Temperature Min (deg F)	6.188	-4.125	-2.865	21.47	23.42	34.06	45.97	43.06	25.48	-1.587	2.804	2.894	**MIN**	-4.13
Air Temperature Max (deg F)	63.99	63.52	71.65	81.25	88.03	100.4	99.14	98.29	95.11	78.94	74.21	62.31	**MAX**	100.4
Relative Humidity Avg (%)	63.76	57.52	58.49	38.81	41.08	22.33	28.77	26.86	32.40	32.07	42.23	56.57	**AVG**	41.74
Relative Humidity Min (%)	9.56	7.59	10.08	0.03	5.63	2.34	3.04	4.39	3.76	2.01	3.62	8.11	**MIN**	0.03
Relative Humidity Max (%)	100.00	97.60	100.00	99.40	99.50	97.20	99.00	96.40	98.10	99.30	100.00	100.00	**MAX**	100
Total Precipitation (inch)	0.65	0.74	2.18	0.59	3.19	0.08	2.40	2.70	1.84	0.27	0.90	0.84	**TOTAL**	16.38
Max Daily Precipitation (inch)	0.20	0.35	0.38	0.18	0.61	0.08	0.85	0.86	0.68	0.13	0.32	0.42	**MAX**	0.86
Soil Temperature Avg (deg F)	38.31	37.43	45.06	57.70	63.61	78.54	84.31	81.52	71.51	57.91	46.96	36.15	**AVG**	58.25
Soil Temperature Min (deg F)	17.89	20.63	26.99	32.00	32.00	47.23	63.16	60.96	40.73	22.00	25.65	16.93	**MIN**	16.93
Soil Temperature Max (deg F)	60.01	63.07	73.44	88.32	96.37	109.90	112.90	113.50	108.60	89.80	73.78	58.21	**MAX**	113.50
Soil Vol Water Content Avg	0.09	0.11	0.14	0.14	0.12	0.11	0.10	0.12	0.10	0.08	0.07	0.09	**AVG**	0.11
Soil Vol Water Content Min	0.06	0.08	0.09	0.09	0.10	0.09	0.08	0.07	0.06	0.05	0.05	0.06	**MIN**	0.05
Soil Vol Water Content Max	0.11	0.16	0.20	0.18	0.17	0.16	0.15	0.20	0.18	0.16	0.11	0.14	**MAX**	0.20

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-5. Station 404 long-term monthly statistics at Clean Slate II (continued).

	Start Date: 4/26/2017; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	229	329	424	555	614	741	656	607	507	408	272	211	**AVG**	462.82
Solar Radiation Max (ly/day)	322	444	585	699	768	791	774	709	619	505	359	277	**MAX**	791
Barometric P. Avg (in Hg)	24.75	24.54	24.63	24.57	24.51	24.55	24.65	24.62	24.57	24.61	24.62	24.71	**AVG**	24.61
Barometric P. Min (in Hg)	24.31	24.09	24.15	24.21	24.13	24.17	24.40	24.37	24.13	24.24	22.88	24.32	**MIN**	22.88
Barometric P. Max (in Hg)	25.11	24.96	24.92	24.93	24.86	24.86	24.91	24.87	24.82	24.96	24.99	25.02	**MAX**	25.11
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	0.56	1.00	1.11	2.38	2.46	2.38	2.56	2.32	2.28	2.06	1.61	0.69	**AVG**	1.79
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	80.10	40.64	221.30	213.00	25.30	79.60	88.30	70.95	163.75	106.50	224.90	187.31	**MAX**	224.90
PM_{10} Avg Concentration ($\mu g/m^3$)	5.04	6.23	8.01	12.50	11.02	16.33	16.88	13.05	13.56	14.84	13.28	6.15	**AVG**	11.41
PM_{10} Max Concentration ($\mu g/m^3$)	7,552.10	445.84	3,457.80	2,273.81	865.00	4,010.60	12,139.40	634.30	858.15	1,990.00	4,315.43	3,202.52	**MAX**	12,139.40

Table B-6. Station 405 long-term monthly statistics at Clean Slate II.

	Start Date: 4/26/2017; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	5.42	7.62	7.23	8.03	7.72	7.29	6.80	6.38	6.47	5.90	5.30	5.44	**AVG**	6.63
Wind Speed Max (mph)	27.1	28.83	33.81	29.52	29.66	28.23	25.94	24.74	27.52	28.85	28.92	30.32	**MAX**	33.81
Wind Speed Gust (mph)	38.43	40.33	48.22	42.6	51.95	50.2	44.57	42.01	39.09	42.96	39.68	41.65	**MAX**	51.95
Wind Freq from S*	33.98%	38.33%	46.22%	22.19%	29.74%	35.63%	45.53%	41.71%	35.27%	16.12%	30.90%	15.98%	**AVG**	32.63%
Wind Freq from NW**	33.77%	35.08%	24.03%	42.86%	36.65%	31.08%	10.10%	8.16%	20.47%	39.24%	27.31%	44.45%	**AVG**	29.43%
Air Temperature Avg (deg F)	34.08	30.39	39.56	50.98	56.35	70.12	76.65	74.05	63.02	47.92	39.12	30.57	**AVG**	51.07
Air Temperature Min (deg F)	3.92	-4.665	-3.981	20.19	21.98	33.86	44.34	40.78	22.78	-4.305	1.634	1.004	**MIN**	-4.67
Air Temperature Max (deg F)	64.31	63.7	71.83	82.76	88.63	100.9	99.86	99.3	95.02	79.11	75.54	63.93	**MAX**	100.9
Relative Humidity Avg (%)	63.53	58.08	59.05	39.00	41.25	22.51	28.86	27.08	32.79	32.57	42.85	57.12	**AVG**	42.06
Relative Humidity Min (%)	9.36	7.74	10.17	3.04	5.98	2.67	2.86	4.51	3.70	2.25	3.56	7.99	**MIN**	2.25
Relative Humidity Max (%)	100.00	100.00	100.00	99.60	99.70	97.70	99.00	97.40	98.40	99.60	100.00	99.90	**MAX**	100
Total Precipitation (inch)	0.47	0.79	2.11	0.66	3.44	0.14	2.38	2.28	1.88	0.28	0.84	0.81	**TOTAL**	16.08
Max Daily Precipitation (inch)	0.14	0.31	0.38	0.17	0.70	0.07	0.70	0.99	0.62	0.10	0.29	0.39	**MAX**	0.99
Soil Temperature Avg (deg F)	37.06	35.59	44.19	59.48	66.81	82.73	89.39	77.10	71.65	55.64	45.00	34.83	**AVG**	58.29
Soil Temperature Min (deg F)	15.89	17.17	22.86	32.00	38.56	47.66	62.83	32.00	38.34	19.47	23.39	14.56	**MIN**	14.56
Soil Temperature Max (deg F)	58.17	58.42	70.95	91.80	100.10	114.10	120.00	117.50	112.00	90.14	71.78	58.73	**MAX**	120.00
Soil Vol Water Content Avg	0.14	0.16	0.20	0.24	0.22	0.21	0.18	0.19	0.17	0.15	0.14	0.14	**AVG**	0.18
Soil Vol Water Content Min	0.09	0.10	0.16	0.13	0.19	0.18	0.16	0.15	0.12	0.10	0.10	0.10	**MIN**	0.09
Soil Vol Water Content Max	0.18	0.19	0.29	0.29	0.26	0.26	0.20	0.26	0.24	0.23	0.20	0.18	**MAX**	0.29

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-6. Station 405 long-term monthly statistics at Clean Slate II (continued).

	Start Date: 4/26/2017; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	255	349	445	564	619	741	656	616	521	434	298	232	**AVG**	477.49
Solar Radiation Max (ly/day)	346	465	614	707	772	792	776	721	643	519	388	302	**MAX**	792
Barometric P. Avg (in Hg)	24.62	24.45	24.50	24.50	24.45	24.53	24.63	24.60	24.55	24.58	24.58	24.61	**AVG**	24.55
Barometric P. Min (in Hg)	24.18	24.03	24.07	24.17	24.13	24.16	24.39	24.38	24.08	24.24	23.94	24.23	**MIN**	23.94
Barometric P. Max (in Hg)	24.95	24.87	24.76	24.81	24.81	24.82	24.81	24.76	24.79	24.97	24.97	24.98	**MAX**	24.98
$PM_{2.5}$ Avg Concentration (µg/m^3)	0.50	1.08	0.91	2.24	1.94	2.22	2.39	2.34	2.07	1.97	1.55	0.70	**AVG**	1.66
$PM_{2.5}$ Max Concentration (µg/m^3)	50.20	59.33	29.03	132.00	136.33	67.50	175.30	53.14	122.69	394.30	284.80	97.21	**MAX**	394.30
PM_{10} Avg Concentration (µg/m^3)	3.76	6.90	7.45	10.63	11.23	17.12	17.23	15.87	14.93	15.02	13.46	6.21	**AVG**	11.65
PM_{10} Max Concentration (µg/m^3)	3,655.10	1,077.10	8,662.50	974.40	1,243.40	881.10	3,426.30	547.03	4,203.20	2,189.80	3,263.90	1,760.21	**MAX**	8,662.50

Table B-7. Plutonium Valley 1 (south) station long-term monthly statistics.

	Start Date: 8/18/2011; End Date: 10/14/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	4.69	5.52	6.07	6.85	6.36	6.37	5.74	5.35	5.38	5.04	4.65	4.67	**AVG**	5.56
Wind Speed Max (mph)	26.42	28.05	38.93	31.09	29.82	26.93	29.43	25.54	25.96	27.23	31.63	30.17	**MAX**	38.93
Wind Speed Gust (mph)	41.5	43.26	55.17	49.54	49.61	44.13	47.93	38.07	49.17	45.01	48.74	46.47	**MAX**	55.17
Wind Freq from S*	27.67%	45.75%	54.09%	47.68%	62.47%	75.18%	76.14%	81.24%	71.66%	47.79%	43.60%	23.70%	**AVG**	54.75%
Wind Freq from NW**	17.60%	23.07%	19.02%	26.00%	14.14%	7.14%	5.03%	2.95%	8.20%	15.48%	17.77%	30.64%	**AVG**	15.59%
Air Temperature Avg (deg F)	39.35	42.03	49.80	56.87	63.62	77.96	81.77	78.95	70.99	58.04	45.46	37.08	**AVG**	58.49
Air Temperature Min (deg F)	3.992	4.856	15.08	20.21	27.76	37.19	46.32	46.17	26.36	23.29	12.43	4.172	**MIN**	3.99
Air Temperature Max (deg F)	71.76	77.94	83.07	91.65	96.57	108.8	108.9	104.6	101	93.33	78.8	71.89	**MAX**	108.9
Relative Humidity Avg (%)	53.60	48.18	41.40	30.61	31.88	16.53	26.16	27.84	28.97	35.11	42.49	52.22	**AVG**	36.25
Relative Humidity Min (%)	0.00	0.34	1.39	0.01	0.68	0.00	1.12	0.28	0.88	1.38	3.06	1.98	**MIN**	0.00
Relative Humidity Max (%)	100.00	99.50	100.00	100.00	98.30	94.50	96.70	99.60	98.30	99.40	98.90	100.00	**MAX**	100
Total Precipitation (inch)	7.12	5.02	4.64	2.75	2.84	0.42	3.20	4.78	2.50	6.05	1.59	3.64	**TOTAL**	44.55
Max Daily Precipitation (inch)	0.80	1.23	1.50	0.49	0.43	0.36	0.51	1.32	0.66	1.44	0.74	0.66	**MAX**	1.50
Soil Temperature Avg (deg F)	39.38	43.38	52.73	63.28	71.69	85.93	89.56	86.10	77.53	61.75	47.84	38.50	**AVG**	63.14
Soil Temperature Min (deg F)	17.89	23.64	28.53	33.35	44.70	55.60	61.14	59.85	45.14	34.59	21.86	15.37	**MIN**	15.37
Soil Temperature Max (deg F)	64.98	73.76	87.60	104.30	115.80	123.40	125.00	118.60	112.60	98.35	80.28	66.94	**MAX**	125.00
Soil Vol Water Content Avg	0.18	0.20	0.20	0.18	0.17	0.14	0.13	0.16	0.15	0.16	0.16	0.16	**AVG**	0.17
Soil Vol Water Content Min	0.09	0.11	0.12	0.13	0.11	0.09	0.08	0.08	0.08	0.08	0.09	0.09	**MIN**	0.08
Soil Vol Water Content Max	0.31	0.31	0.35	0.24	0.24	0.22	0.25	0.36	0.35	0.36	0.26	0.31	**MAX**	0.36

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-7. Plutonium Valley 1 (south) station long-term monthly statistics (continued).

	Start Date: 8/18/2011; End Date: 10/14/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	212	305	406	511	517	573	494	489	443	349	244	185	**AVG**	393.97
Solar Radiation Max (ly/day)	338	478	577	658	694	727	624	641	587	505	363	292	**MAX**	727
Barometric P. Avg (in Hg)	25.95	25.86	25.85	25.79	25.76	25.77	25.41	25.07	25.82	25.86	25.91	25.91	**AVG**	25.75
Barometric P. Min (in Hg)	25.14	25.12	25.33	25.27	25.39	25.49	17.72	17.72	25.39	25.30	25.32	25.33	**MIN**	17.72
Barometric P. Max (in Hg)	26.41	26.29	26.25	26.19	26.26	26.12	26.06	26.03	26.15	26.24	26.34	26.31	**MAX**	26.41
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	0.57	1.25	1.49	3.51	2.99	3.60	4.58	3.48	2.90	1.99	1.44	0.90	**AVG**	2.39
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	13.08	158.08	450.14	1,207.44	27.23	81.32	386.26	192.00	70.16	60.48	88.43	152.92	**MAX**	1,207.44
PM_{10} Avg Concentration ($\mu g/m^3$)	1.65	3.34	4.88	12.31	11.46	17.31	18.95	14.18	12.32	8.41	6.18	3.42	**AVG**	9.53
PM_{10} Max Concentration ($\mu g/m^3$)	130.90	275.07	2,571.36	5,967.81	326.95	506.70	1,121.45	401.37	196.34	475.84	408.26	1,066.39	**MAX**	5,967.81

Table B-8. Plutonium Valley 2 (north) station long-term monthly statistics.

	Start Date: 8/22/2011; End Date: 10/14/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	5.05	5.66	6.29	6.81	6.38	6.33	5.61	5.35	5.33	5.22	4.91	5.14	**AVG**	5.67
Wind Speed Max (mph)	25.62	26.38	34.85	31.65	30.41	28.41	27.21	25.38	27.81	26.03	29.82	26.89	**MAX**	34.85
Wind Speed Gust (mph)	40.7	41.79	53.63	46.98	51.22	43.04	49.61	39.24	51.88	40.7	43.91	46.98	**MAX**	53.63
Wind Freq from S*	21.22%	37.52%	50.53%	45.08%	56.40%	72.14%	74.10%	80.00%	64.08%	39.93%	35.45%	16.16%	**AVG**	49.38%
Wind Freq from NW**	43.58%	41.69%	31.92%	39.19%	25.47%	15.40%	10.41%	8.06%	18.32%	35.34%	39.19%	54.57%	**AVG**	30.26%
Air Temperature Avg (deg F)	39.93	42.11	49.70	56.77	63.95	77.40	81.25	78.94	71.05	58.50	45.79	37.69	**AVG**	58.59
Air Temperature Min (deg F)	2.48	4.01	14.63	20.08	28.84	36.96	47.17	45.1	25.99	23.8	11.3	5.774	**MIN**	2.48
Air Temperature Max (deg F)	71.71	78.06	82.02	91.51	96.48	107.9	108	104.4	101.4	92.91	79.56	70.86	**MAX**	108
Relative Humidity Avg (%)	49.12	45.84	39.24	29.72	29.54	15.86	25.74	26.43	27.88	33.23	40.60	48.63	**AVG**	34.32
Relative Humidity Min (%)	0.03	0.26	1.38	0.00	0.38	0.00	1.11	0.12	1.08	1.11	2.62	1.91	**MIN**	0.00
Relative Humidity Max (%)	100.00	99.40	100.00	99.90	98.00	92.00	96.50	97.50	97.30	98.70	100.00	100.00	**MAX**	100
Total Precipitation (inch)	6.59	4.24	4.18	2.26	2.98	0.55	3.26	3.78	1.73	6.50	1.37	3.26	**TOTAL**	40.7
Max Daily Precipitation (inch)	0.79	0.99	1.18	0.44	0.46	0.43	0.35	1.70	0.29	1.37	0.53	0.42	**MAX**	1.70
Soil Temperature Avg (deg F)	39.79	43.59	52.70	63.35	72.70	85.77	89.77	86.35	77.41	62.25	48.34	39.15	**AVG**	63.43
Soil Temperature Min (deg F)	23.03	28.06	31.44	38.01	46.90	58.12	65.03	65.50	50.72	39.12	28.79	22.29	**MIN**	22.29
Soil Temperature Max (deg F)	57.24	64.62	78.66	95.59	107.20	115.50	117.40	112.80	105.30	93.13	72.79	58.86	**MAX**	117.40

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-8. Plutonium Valley 2 (north) station long-term monthly statistics (continued).

	Start Date: 8/22/2011; End Date: 10/14/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Soil Vol Water Content Avg	0.08	0.08	0.08	0.07	0.06	0.05	0.05	0.06	0.06	0.08	0.07	0.08	**AVG**	0.07
Soil Vol Water Content Min	0.04	0.05	0.06	0.04	0.04	0.03	0.03	0.02	0.03	0.03	0.04	0.04	**MIN**	0.02
Soil Vol Water Content Max	0.21	0.21	0.22	0.19	0.16	0.09	0.16	0.27	0.13	0.30	0.16	0.18	**MAX**	0.30
Solar Radiation Avg (ly/day)	253	343	422	554	623	688	635	583	469	385	293	231	**AVG**	456.55
Solar Radiation Max (ly/day)	366	457	534	669	739	758	738	689	608	466	377	296	**MAX**	758
Barometric P. Avg (in Hg)	26.64	26.54	26.52	26.47	26.42	26.44	26.53	26.30	26.15	26.55	26.59	26.60	**AVG**	26.48
Barometric P. Min (in Hg)	25.82	25.95	25.87	25.91	25.95	26.14	26.25	17.54	17.49	25.95	26.08	25.98	**MIN**	17.49
Barometric P. Max (in Hg)	27.13	27.01	26.96	26.89	26.96	26.82	26.75	26.74	26.85	26.96	27.01	27.03	**MAX**	27.13
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	2.48	4.66	5.49	6.00	6.61	7.08	6.19	6.96	6.25	2.77	2.13	3.59	**AVG**	5.02
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	24.08	145.71	101.83	516.88	45.93	65.45	404.59	132.98	84.10	60.95	75.07	124.33	**MAX**	516.88
PM_{10} Avg Concentration ($\mu g/m^3$)	3.53	7.13	8.51	12.31	12.94	17.83	19.12	17.91	16.56	8.57	5.77	5.55	**AVG**	11.31
PM_{10} Max Concentration ($\mu g/m^3$)	59.18	318.01	461.84	2,707.23	300.09	316.57	1,252.23	555.72	373.12	396.51	312.92	815.93	**MAX**	2,707.23

Table B-9. Smoky station long-term monthly statistics.

	Start Date: 7/14/2011; End Date: 10/15/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	4.97	6.00	6.79	7.67	7.09	6.84	6.17	5.74	5.73	5.57	5.20	5.26	**AVG**	6.09
Wind Speed Max (mph)	29.67	30.74	43.46	34.71	30.28	25.75	29.03	32.14	30.1	30.02	35.75	36.19	**MAX**	43.46
Wind Speed Gust (mph)	53.34	49.17	60.72	53.78	45.52	49.1	44.06	45.81	45.45	62.98	53.63	56.77	**MAX**	62.98
Wind Freq from S*	18.53%	27.24%	37.43%	30.93%	40.16%	52.98%	60.68%	63.64%	43.89%	32.35%	27.99%	15.56%	**AVG**	37.62%
Wind Freq from NW**	26.07%	31.46%	24.21%	32.37%	23.54%	12.62%	12.29%	8.53%	13.21%	17.35%	25.67%	34.30%	**AVG**	21.80%
Air Temperature Avg (deg F)	40.54	43.09	50.53	57.75	64.67	78.92	81.36	79.81	72.15	59.85	47.41	38.91	**AVG**	59.58
Air Temperature Min (deg F)	3.29	10.8	19.39	27.3	33.9	43.61	54	53.89	31.86	28.8	17.49	8.312	**MIN**	3.29
Air Temperature Max (deg F)	71.47	75.02	81.86	90.25	95.23	108	107.5	103	99.81	93.88	78.28	70.32	**MAX**	108
Relative Humidity Avg (%)	49.20	44.95	38.07	28.45	28.57	14.92	26.37	25.80	27.14	31.63	37.81	46.43	**AVG**	33.28
Relative Humidity Min (%)	3.40	0.63	2.05	0.00	0.60	0.00	1.23	0.89	1.47	0.00	2.47	2.51	**MIN**	0.00
Relative Humidity Max (%)	100.00	100.00	99.90	100.00	97.40	95.60	98.10	100.00	97.90	98.20	98.20	100.00	**MAX**	100
Total Precipitation (inch)	7.85	5.88	4.13	2.57	2.70	0.69	7.46	6.38	2.57	7.17	0.84	3.54	**TOTAL**	51.78
Max Daily Precipitation (inch)	0.78	1.23	1.16	0.48	0.26	0.05	1.38	1.90	0.65	2.44	0.22	0.68	**MAX**	2.44
Soil Temperature Avg (deg F)	41.08	46.06	55.11	65.86	74.61	89.17	90.59	88.74	79.77	65.49	51.04	40.49	**AVG**	65.67
Soil Temperature Min (deg F)	16.11	26.29	30.62	36.56	47.14	57.88	62.55	63.03	50.32	32.00	26.39	20.07	**MIN**	16.11
Soil Temperature Max (deg F)	65.61	76.12	92.23	102.20	115.10	122.80	124.70	117.90	111.00	101.00	80.98	64.83	**MAX**	124.70
Soil Vol Water Content Avg	0.15	0.15	0.15	0.14	0.14	0.12	0.14	0.14	0.12	0.13	0.11	0.12	**AVG**	0.13
Soil Vol Water Content Min	0.07	0.08	0.10	0.10	0.09	0.09	0.08	0.07	0.07	0.00	0.07	0.06	**MIN**	0.00
Soil Vol Water Content Max	0.28	0.32	0.33	0.24	0.20	0.18	0.25	0.30	0.25	0.31	0.18	0.25	**MAX**	0.33

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-9. Smoky station long-term monthly statistics (continued).

	Start Date: 7/14/2011; End Date: 10/15/201													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	271	372	488	618	677	760	682	632	546	429	313	248	**AVG**	502.87
Solar Radiation Max (ly/day)	382	513	653	766	803	821	807	769	678	553	419	323	**MAX**	821
Barometric P. Avg (in Hg)	25.65	25.56	25.55	25.50	25.47	25.48	25.56	25.56	25.55	25.58	25.61	25.61	**AVG**	25.56
Barometric P. Min (in Hg)	24.89	24.99	24.93	24.99	25.04	25.21	25.32	25.35	25.09	25.04	25.13	25.06	**MIN**	24.89
Barometric P. Max (in Hg)	26.10	25.98	25.95	25.89	25.96	25.70	25.76	25.75	25.85	25.96	26.03	26.01	**MAX**	26.1
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**AVG**	NA
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**MAX**	NA
PM_{10} Avg Concentration ($\mu g/m^3$)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**AVG**	NA
PM_{10} Max Concentration ($\mu g/m^3$)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**MAX**	NA

NA = data not available.

Table B-10. Project 57 Station 503 long-term monthly statistics.

	Start Date: 1/7/2015; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	8.22	9.05	8.69	9.49	8.34	8.53	7.59	7.14	7.73	8.04	7.49	8.39	**AVG**	8.23
Wind Speed Max (mph)	41.64	39.43	38.62	37.3	33.94	32.91	26.5	32.75	28.46	33.52	38.28	38.75	**MAX**	41.64
Wind Speed Gust (mph)	63	52.9	57.6	54.5	50.4	48.4	51.2	52.2	42.8	47.4	50.6	68.2	**MAX**	68.2
Wind Freq from S*	16.83%	27.63%	34.02%	29.74%	39.93%	49.35%	54.48%	53.36%	44.15%	22.00%	20.30%	10.42%	**AVG**	33.52%
Wind Freq from NW**	54.71%	51.73%	45.30%	46.94%	37.85%	31.94%	27.33%	30.36%	38.15%	50.35%	51.87%	58.38%	**AVG**	43.74%
Air Temperature Avg (deg F)	37.71	40.11	47.26	53.93	60.20	75.20	78.49	76.37	67.83	55.16	42.92	35.15	**AVG**	55.86
Air Temperature Min (deg F)	11.17	4.316	12.79	19.9	27.64	38.34	43.7	43.2	25.21	12.94	1.832	7.16	**MIN**	1.83
Air Temperature Max (deg F)	70.47	75.36	82.89	88.03	93.78	106.1	107.1	103.7	100	90.34	80.74	71.08	**MAX**	107.1
Relative Humidity Avg (%)	62.20	52.24	44.45	35.12	37.48	18.47	24.62	24.00	26.06	34.10	41.68	52.59	**AVG**	37.75
Relative Humidity Min (%)	3.74	7.04	5.85	4.25	4.89	2.66	3.48	3.07	3.10	2.99	4.18	6.05	**MIN**	2.66
Relative Humidity Max (%)	100.00	100.00	100.00	98.80	98.80	93.80	98.20	99.50	95.10	98.20	100.00	100.00	**MAX**	100
Total Precipitation (inch)	4.76	3.17	3.47	2.33	2.25	0.58	1.44	1.00	1.57	2.97	1.79	2.36	**TOTAL**	27.69
Max Daily Precipitation (inch)	0.71	0.75	1.17	0.41	0.30	0.52	0.35	0.30	0.79	0.85	0.81	0.62	**MAX**	1.17
Soil Temperature Avg (deg F)	37.35	40.40	48.20	56.64	63.81	78.47	83.20	81.50	72.60	57.26	44.94	36.25	**AVG**	58.39
Soil Temperature Min (deg F)	25.12	24.20	28.82	41.60	44.44	54.88	66.27	62.28	47.93	31.66	28.47	25.54	**MIN**	24.20
Soil Temperature Max (deg F)	53.31	58.53	69.01	75.96	88.12	99.19	101.30	99.72	93.97	78.76	65.98	50.95	**MAX**	101.30
Soil Vol Water Content Avg	0.13	0.14	0.14	0.12	0.10	0.10	0.08	0.07	0.08	0.09	0.09	0.10	**AVG**	0.10
Soil Vol Water Content Min	0.07	0.09	0.09	0.08	0.09	0.07	0.07	0.06	0.05	0.05	0.05	0.06	**MIN**	0.05
Soil Vol Water Content Max	0.21	0.23	0.22	0.15	0.15	0.15	0.11	0.10	0.21	0.25	0.18	0.20	**MAX**	0.25

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-10. Project 57 Station 503 long-term monthly statistics (continued).

	Start Date: 1/7/2015; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	234	331	428	530	582	684	620	574	502	399	288	224	**AVG**	449.69
Solar Radiation Max (ly/day)	354	475	584	683	732	754	742	676	602	511	377	313	**MAX**	754
Barometric P. Avg (in Hg)	25.44	25.38	25.38	25.33	25.28	25.34	25.41	25.40	25.37	25.41	25.42	25.41	**AVG**	25.38
Barometric P. Min (in Hg)	24.70	23.98	24.84	25.01	23.12	25.00	25.15	25.19	24.94	24.93	24.86	24.67	**MIN**	23.12
Barometric P. Max (in Hg)	25.90	25.79	25.72	25.70	25.64	25.66	25.61	25.57	25.68	25.79	25.85	25.82	**MAX**	25.9
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	0.38	1.00	0.89	3.12	1.86	1.99	2.49	2.48	1.82	1.22	0.89	0.55	**AVG**	1.56
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	27.09	118.17	90.41	1,365.29	76.19	63.04	137.10	191.30	141.96	154.57	56.24	95.68	**MAX**	1,365.29
PM_{10} Avg Concentration ($\mu g/m^3$)	3.62	9.21	9.52	39.03	13.24	18.30	21.17	24.77	20.44	13.43	8.66	5.08	**AVG**	15.54
PM_{10} Max Concentration ($\mu g/m^3$)	1,769.79	6,038.57	1,735.11	27,398.34	1,006.95	1,881.34	4,208.61	4,616.33	16,563.29	902.79	1,646.11	1,123.06	**MAX**	27,398.34

Table B-11. Project 57 Station 504 long-term monthly statistics.

	Start Date: 1/6/2015; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Wind Speed Avg (mph)	7.28	8.09	7.89	8.86	7.80	8.10	7.15	6.68	7.19	7.37	6.40	6.17	**AVG**	7.41
Wind Speed Max (mph)	28.09	29.72	35.85	35.25	32.17	30.06	27.27	29.86	27.84	29.55	32.06	29.65	**MAX**	35.85
Wind Speed Gust (mph)	46	42.2	51.8	50.2	49.5	47.2	45.2	45.5	50.5	44.9	47.7	43.7	**MAX**	51.8
Wind Freq from S*	16.95%	27.42%	33.28%	27.43%	35.47%	42.19%	52.66%	52.62%	41.28%	22.53%	20.37%	11.45%	**AVG**	31.97%
Wind Freq from NW**	42.51%	40.98%	38.54%	41.72%	35.60%	29.95%	21.50%	21.09%	33.29%	49.77%	52.21%	60.52%	**AVG**	38.97%
Air Temperature Avg (deg F)	38.00	40.36	47.59	54.43	60.48	75.44	78.69	76.58	68.06	55.30	42.82	35.19	**AVG**	56.08
Air Temperature Min (deg F)	11.5	3.056	13.06	19.97	26.32	37.28	42.45	43.39	26.32	10.22	-0.78	6.30	**MIN**	-0.78
Air Temperature Max (deg F)	71.51	76.44	83.08	88.72	94.26	106.9	107.9	103.8	100.9	89.58	78.89	70.07	**MAX**	107.9
Relative Humidity Avg (%)	64.07	54.61	46.64	36.85	39.96	20.50	27.31	26.63	28.42	36.53	43.71	54.68	**AVG**	39.99
Relative Humidity Min (%)	3.76	6.67	5.07	3.65	4.52	1.12	2.58	1.93	2.29	2.02	3.34	6.47	**MIN**	1.12
Relative Humidity Max (%)	100.00	100.00	99.70	99.30	99.30	96.70	99.60	98.20	98.40	99.20	99.80	100.00	**MAX**	100
Total Precipitation (inch)	4.95	4.18	3.05	1.74	2.26	0.54	2.01	1.35	1.59	2.73	1.65	2.40	**TOTAL**	28.45
Max Daily Precipitation (inch)	0.54	0.79	1.00	0.36	0.26	0.49	0.44	0.39	0.97	0.82	0.73	0.56	**MAX**	1.00
Soil Temperature Avg (deg F)	37.48	41.78	51.15	61.24	68.52	83.91	87.84	85.39	75.53	59.34	45.29	36.16	**AVG**	61.14
Soil Temperature Min (deg F)	21.68	24.78	29.11	37.43	43.48	55.58	60.55	61.27	48.06	29.15	22.69	21.27	**MIN**	21.27
Soil Temperature Max (deg F)	73.35	67.78	79.20	89.20	97.97	111.10	114.50	110.10	101.20	84.20	72.10	54.54	**MAX**	114.50
Soil Vol Water Content Avg	0.17	0.18	0.19	0.18	0.17	0.15	0.12	0.12	0.11	0.13	0.12	0.14	**AVG**	0.15
Soil Vol Water Content Min	0.09	0.13	0.14	0.14	0.14	0.11	0.10	0.08	0.07	0.06	0.07	0.09	**MIN**	0.06
Soil Vol Water Content Max	0.28	0.29	0.30	0.25	0.25	0.20	0.18	0.18	0.31	0.34	0.22	0.26	**MAX**	0.34

*Wind Freq from S (indicates aggregate frequency for winds over 5 mph coming from the south direction).

**Wind Freq from NW (indicates aggregate frequency for winds over 5 mph coming from the northwest direction).

Table B-11. Project 57 Station 504 long-term monthly statistics (continued).

	Start Date: 1/6/2015; End Date: 12/31/2019													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**Value**
Solar Radiation Avg (ly/day)	241	339	446	559	595	694	636	596	520	399	296	231	**AVG**	462.68
Solar Radiation Max (ly/day)	353	463	595	697	750	778	760	693	620	507	385	302	**MAX**	778
Barometric P. Avg (in Hg)	25.46	25.40	25.40	25.36	25.32	25.38	25.45	25.44	25.41	25.44	25.44	25.45	**AVG**	25.41
Barometric P. Min (in Hg)	24.71	24.82	24.88	25.03	24.98	25.06	25.20	25.23	24.98	23.89	24.87	24.91	**MIN**	23.89
Barometric P. Max (in Hg)	25.92	25.82	25.74	25.74	25.69	25.70	25.66	25.62	25.71	25.83	25.88	25.84	**MAX**	25.92
$PM_{2.5}$ Avg Concentration ($\mu g/m^3$)	0.39	1.09	1.25	2.81	2.15	2.56	2.97	2.34	1.82	1.27	0.93	0.54	**AVG**	1.68
$PM_{2.5}$ Max Concentration ($\mu g/m^3$)	30.88	111.02	44.47	497.46	55.90	137.13	214.26	153.97	80.39	134.80	66.88	51.24	**MAX**	497.46
PM_{10} Avg Concentration ($\mu g/m^3$)	3.58	9.80	9.13	21.01	14.86	20.54	22.75	20.25	18.05	12.47	10.15	6.29	**AVG**	14.07
PM_{10} Max Concentration ($\mu g/m^3$)	5,478.94	12,270.24	2,758.79	4,683.56	8,193.44	4,524.11	11,556.77	12,157.22	14,733.98	5,985.35	1,863.39	2,122.64	**MAX**	14,733.98

APPENDIX C. WIND, DUST, AND ASSOCIATED RADIONUCLIDE TRANSPORT MEASURED AT THE SOILS ACTIVITY SITES

Prepared by George Nikolich

SUMMARY OF FINDINGS COMMON TO THE MONITORED SOILS ACTIVITY SITES

Winds from the north, northwest, and south occur most frequently at the Smoky Site, Plutonium Valley, Project 57, and the Clean Slate I, II, and III monitoring stations. Additionally, over 85 percent of the sustained winds over 15 mph at each site (which is considered a lower limit for suspending local soil material) blow from the north, northwest, and south. Sustained winds over 15 mph are more frequent in the spring. March and April have the highest frequency of wind speeds greater than 25 mph during the year. During most of the year, high, sustained winds from the south occur more commonly than winds from the north and northwest. The frequency of north and northwest winds increases between October and March.

Dust suspended and transported by wind usually has an aerodynamic diameter of smaller than 20 µm, but fine particles of less than 10 µm (PM_{10}) are considered small enough to be potentially inhaled by humans. When wind speeds are lower than 15 mph, average PM_{10} concentrations are relatively insensitive to wind and are generally below 20 $\mu g/m^3$, reflecting the relatively clean, remote setting for these sites. Occasional observed increases in the PM_{10} concentration during periods when wind speed is below 15 mph may be the result of local disturbances, such as off-road and unpaved-road vehicle use. Long-range transport of PM_{10} from strong thunderstorm outflows is another potential source of PM_{10} spikes under low wind-speed conditions. For sustained winds between 15 mph and 30 mph, PM_{10} concentration increases approximately exponentially with wind speed. The PM_{10} concentration can exceed 1,000 $\mu g/m^3$ for winds above 30 mph. These moderate and high winds are sufficient to cause local saltation activity and result in transport and suspension of fine dust from the sites.

Monitoring stations positioned north of the contamination areas register more frequent and higher concentration PM_{10} transport events; these sites are downwind from the contamination areas during the frequent southerly winds. More precipitation, lower air temperatures, higher relative humidity, and higher soil water content during winter months at the Clean Slate stations (compared with Project 57 and Plutonium Valley), result in comparatively lower PM_{10} emissions than at the other sites during the same period.

Contaminant migration has been recorded at the Soils Activity sites with air sampling equipment (Project 57 and Clean Slate sites). Project 57 monitoring stations registered increased gross alpha readings downwind from ground zero areas during strong winds, even in the absence of recent ground disturbance. In contrast, the Clean Slate II and III monitoring stations have registered elevated gross alpha concentrations, but those observations are associated with periods when the sites were actively being remediated. Factors responsible

for greater radionuclide transport at Project 57 may include the very-fine-grained and friable nature of the Project 57 soils, the amount and distribution of contamination, and the greater amount of precipitation at the Clean Slate locations relative to Project 57.

Observations specific to each site are provided below. The characteristics of wind speed, direction, and frequency are available for all the sites. Dust movement was measured at Plutonium Valley, the Clean Slate sites, and Project 57 site. Radionuclide transport associated with aeolian (wind-borne) dust movement is also available for the Clean Slate and Project 57 sites. The sites are presented in order of increasing data complexity, beginning with the Smoky Site and followed by Plutonium Valley, Project 57, and the Clean Slate sites. Tables C-1a and C-1b summarize the monitoring stations, periods of operation, and instrumentation.

Smoky Site

The data summarized for the Smoky Site were collected from mid-July 2011 until mid-October 2019, when the station was dismantled and removed. The Smoky Site station was a single meteorological station on the west side of the contamination area (Figure C-1) with a full suite of sensors to measure wind speed, wind direction, air temperature, air relative humidity, barometric pressure, soil temperature, soil volumetric water content, and solar radiation. The station was not equipped with an aerosol/dust monitoring instrument nor suspended dust or saltation samplers because the focus at that site was waterborne transport of radionuclides through ephemeral channels. The station location was selected so that it could be accessed outside of the contamination area.

Table C-1a. Instrumentation and operation dates for monitoring stations at the TTR Range Operation Center and Clean Slate sites. All stations other than Station 402 remain currently in operation, so only Station 402 shows end dates.

Site	**TTR Range Operation Center**	**Clean Slate I**	**Clean Slate II**	**Clean Slate II**	**Clean Slate III**	**Clean Slate III**
Instrument/Measurement	**Station 400**	**Station 402**	**Station 404**	**Station 405**	**Station 401**	**Station 403**
Wind speed	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	6/10/2008	4/25/2017
Wind direction	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	12/22/2009	4/25/2017
Precipitation	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	12/22/2009	4/25/2017
Air temperature	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	6/10/2008	4/25/2017
Relative humidity	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	6/10/2008	4/25/2017
Solar radiation	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	N/A	4/25/2017
Barometric pressure	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	N/A	4/25/2017
Soil temperature	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	12/22/2009	4/25/2017
Soil moisture content	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	12/22/2009	4/25/2017
Airborne particle size profiler	5/27/2008	5/18/2011–4/24/2017	4/25/2017	4/25/2017	6/10/2008	4/25/2017
Airborne particle collector	5/27/2008	8/23/2011–4/24/2017	4/25/2017	4/25/2017	7/30/2008	4/25/2017
Saltation sensor	N/A	8/9/2011–4/24/2017	4/25/2017	4/25/2017	8/9/2011	4/25/2017
Gamma rad. PIC	5/27/2008	12/15/2011–4/24/2017	N/A	N/A	12/22/2009	4/25/2017
Thermoluminescent dosimeter	N/A	N/A	N/A	N/A		N/A
Saltation traps	N/A	4/1/2014–4/24/2017	4/25/2017	4/24/2017		4/25/2017

N/A = not applicable.

Table C-1b. Instrumentation and operation dates for monitoring stations at Project 57. These stations are no longer in operation.

Site	**Project 57**	**Project 57**	**Project 57**	**Project 57**
Instrument/ Measurement	**Station 501**	**Station 502**	**Station 503**	**Station 504**
Wind speed	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Wind direction	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Precipitation	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Air temperature	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Relative humidity	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Solar radiation	N/A	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Barometric pressure	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Soil temperature	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Soil moisture content	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Airborne particle size profiler	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Airborne particle collector	8/11/2011–1/7/2015	11/18/2011–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Saltation sensor	1/9/2012–1/7/2015	1/9/2012 1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Gamma rad. PIC	N/A	N/A	N/A	N/A
Thermoluminescent dosimeter	1/9/2012–1/7/2015	1/9/2012–1/7/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020
Saltation traps	4/14/2014–3/3/2015	4/14/2014–3/3/2015	1/7/2015–10/16/2020	1/7/2015–10/16/2020

N/A = not applicable.

Table C-1c. Instrumentation and operation dates for monitoring stations at the Smoky Site and Plutonium Valley. These stations are no longer in operation.

Site	**Smoky**	**Plutonium Valley**	**Plutonium Valley**
Instrument/ Measurement	**Smoky**	**Plutonium Valley 1 (South)**	**Plutonium Valley 2 (North)**
Wind speed	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Wind direction	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Precipitation	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Air temperature	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Relative humidity	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Solar radiation	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Barometric pressure	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Soil temperature	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Soil moisture content	7/14/2011–10/13/2019	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Airborne particle size profiler	N/A	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Airborne particle collector	N/A	8/24/2011–10/13/2019	8/25/2011–10/13/2019
Saltation sensor	N/A	N/A	N/A
Gamma rad. PIC	N/A	N/A	8/25/2011–10/13/2019
Thermoluminescent dosimeter	N/A	N/A	N/A
Saltation traps	N/A	N/A	N/A

N/A = not applicable.

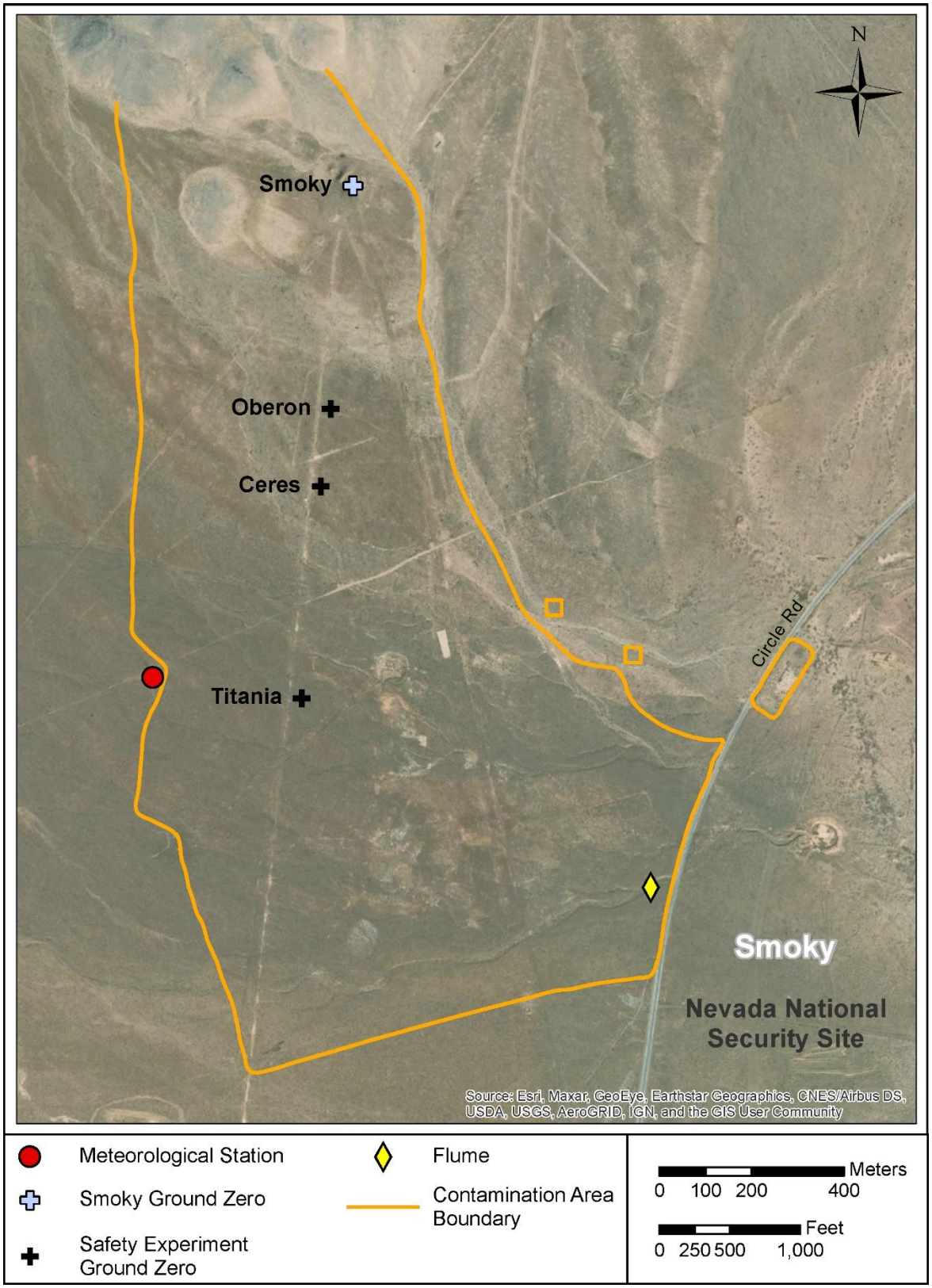

Figure C-1. Location of the meteorological station and flume relative to the Smoky Site contamination area.

Wind Speed and Direction

Wind rose graphs are used to analyze the wind speed and direction for the Smoky Site and the other sites. Wind roses classify wind conditions into 16 directional classes that each span 22.5-degree wedges of the circle. The colors within each wedge represent different wind speed ranges and the length of the wedge represents the frequency of occurrence of the direction/speed-class combination. Two wind roses are shown here for each of the time periods considered. The wind rose on the left shows the direction and wind speed for all winds in 5 mph wind-speed increments. The wind rose on the right displays only data corresponding to wind speeds greater than 15 mph in 3 mph intervals. This is intended to highlight winds above 15 mph, corresponding to a nominal lower limit for windblown dust suspension. The data used in these graphs are from the 10-minute average measurements. Separate wind roses are presented for each quarter of the year to highlight seasonal differences.

At the Smoky Site, frequent light winds between 0 and 10 mph are observed from all directions (red and yellow wedges in the upper left wind rose of Figure C-2). Distribution of wind speeds over 15 mph is strongly associated with the north, northwest, and south wind directions. During the year, virtually none of the winds greater than 15 mph come from the east to southeast (less than one percent) (Figure C-3). Sustained winds over 15 mph are mainly from the south during the second and third quarters of the year (April to September).

The period between March and June has the highest frequency of winds greater than 15 mph (Figure C-4) and on average for the period of record, those four months account for 50 percent of the greater than 15 mph winds. Conversely, August has the lowest frequency of winds greater 15 mph. March and April account for 55 percent of the winds over 25 mph (Figure C-5). For the nine years (3,015 days) of monitoring, winds greater than 15 mph occurred 5.5 percent of the time (165 days) (Figure C-6).

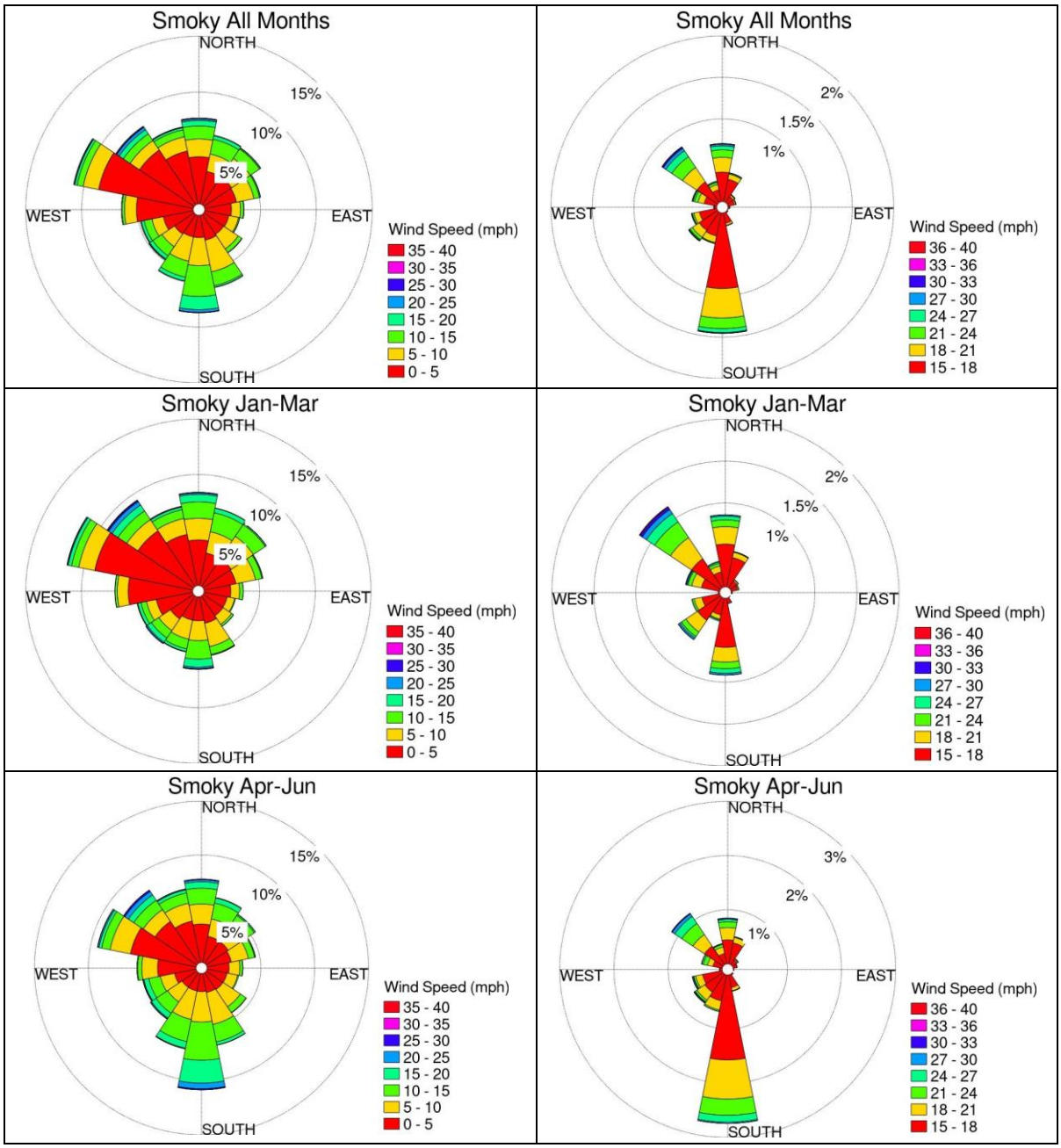

Figure C-2. Smoky station wind roses for July 2011 to October 2019 for all months (top row) and quarterly. The left panel plots all winds and the right panel displays data for only winds greater than 15 mph.

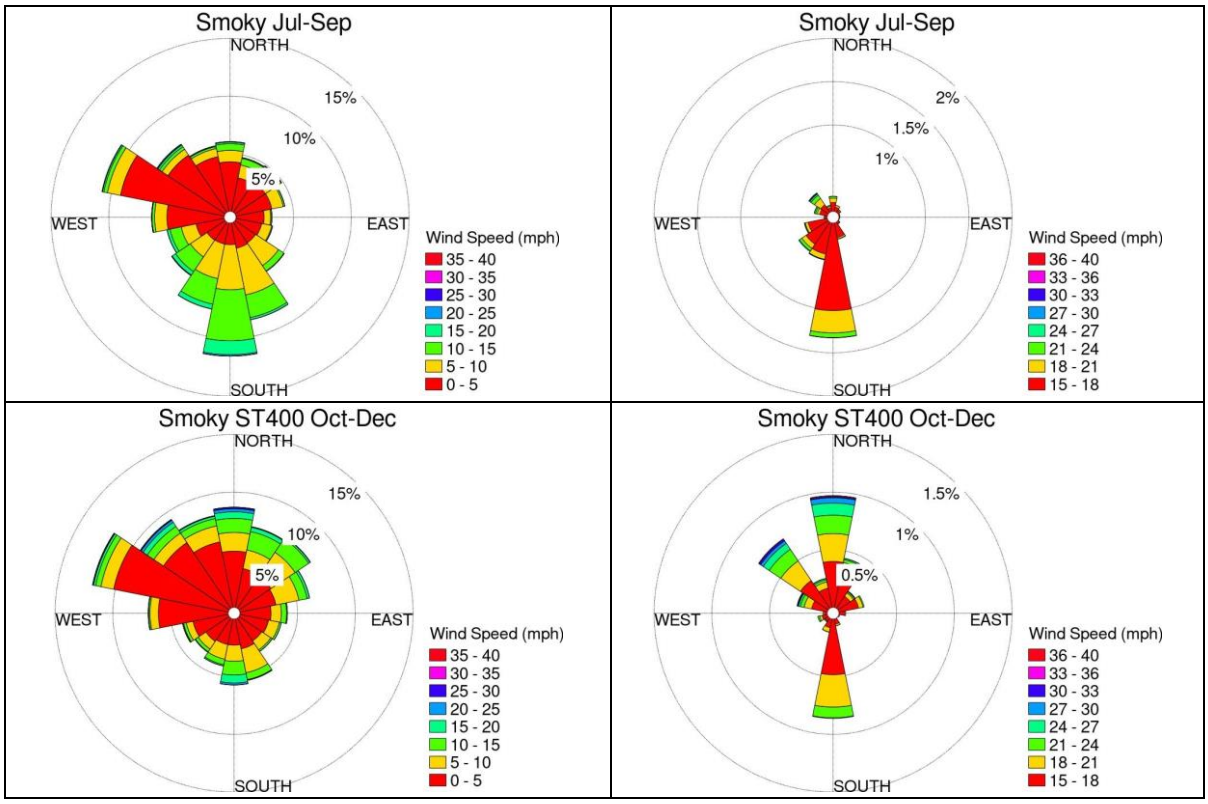

Figure C-2. Smoky station wind roses for July 2011 to October 2019 for all months (top row) and quarterly. The left panel plots all winds and the right panel displays data for only winds greater than 15 mph (continued).

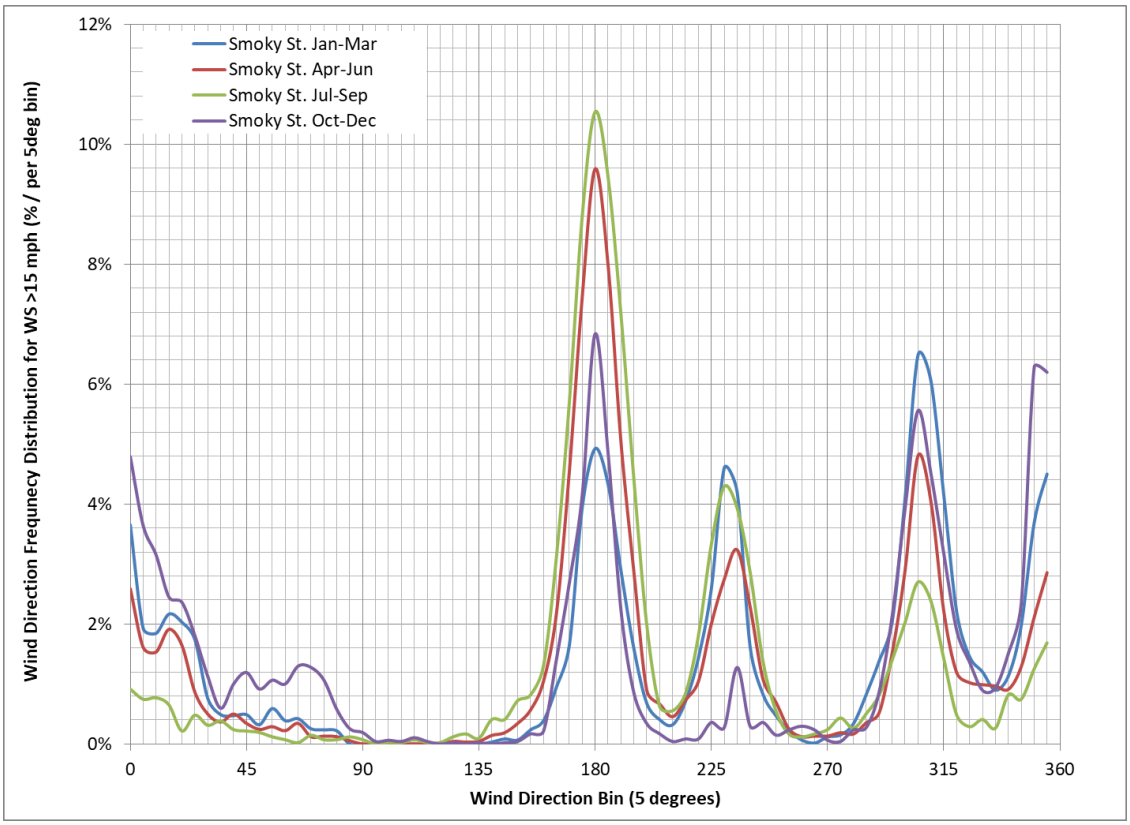

Figure C-3. Wind direction frequency for each three-month period at the Smoky station for data collected from July 2011 to October 2019.

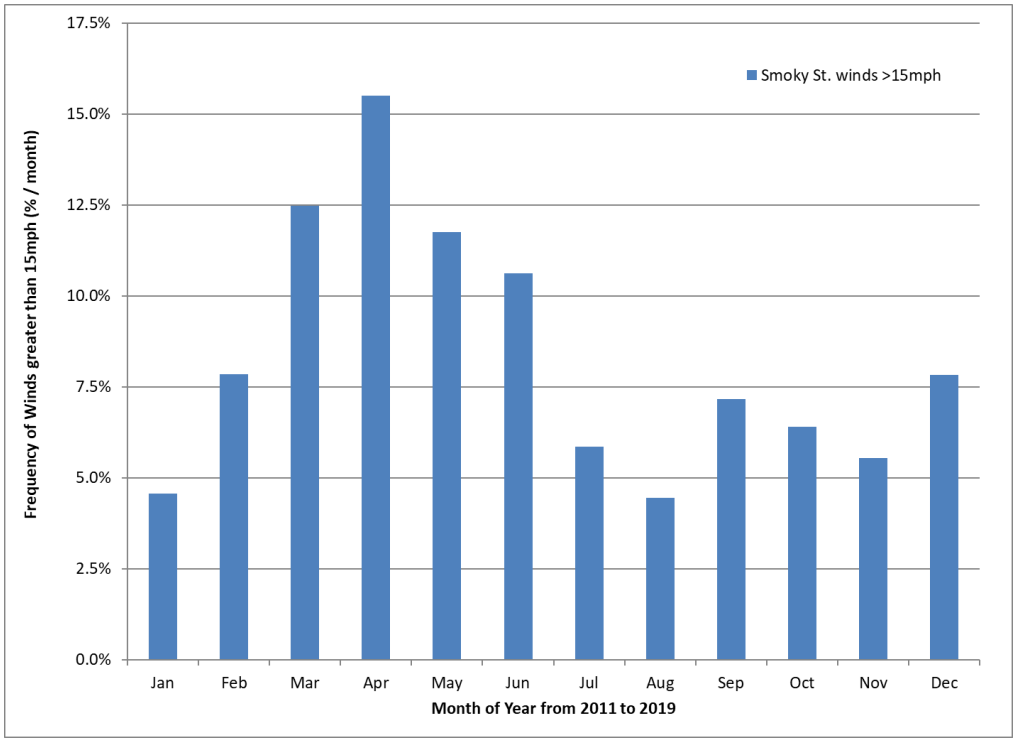

Figure C-4. Monthly wind frequency distribution of winds over 15 mph from July 2011 to October 2019.

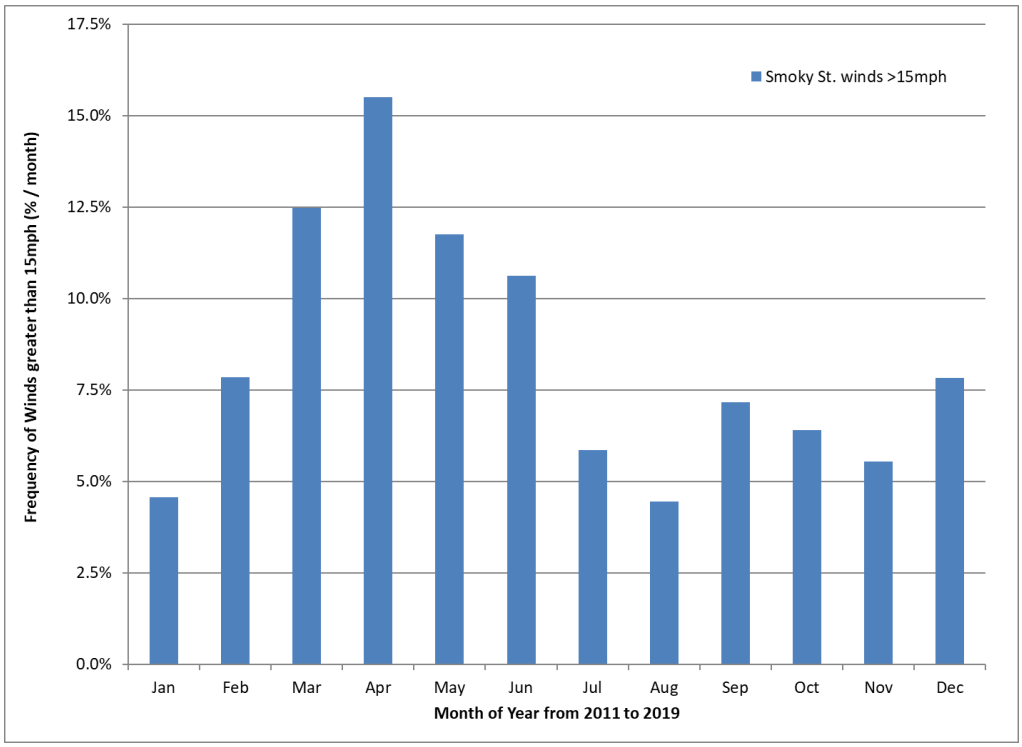

Figure C-5. Monthly wind frequency distribution of winds over 25 mph from July 2011 to October 2019.

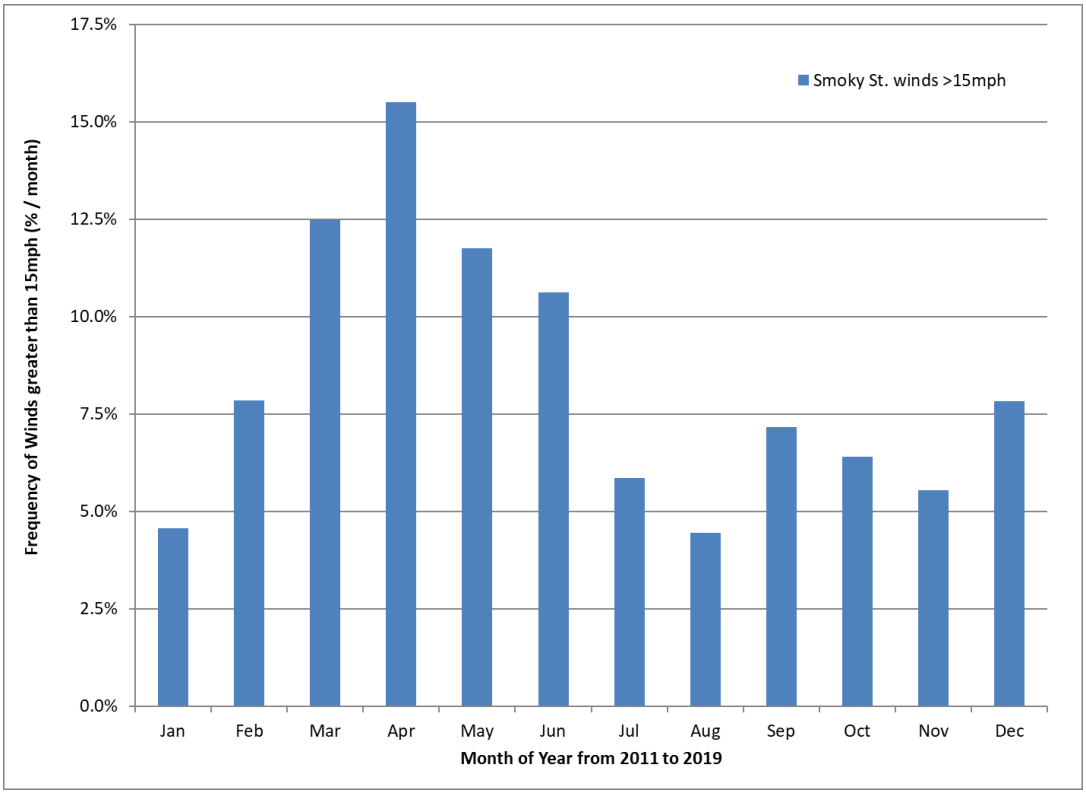

Figure C-6. Wind frequency distribution by 5 mph wind speed class for data collected from July 2011 to October 2019.

Plutonium Valley

The data summarized for Plutonium Valley were collected from the beginning of 2015 to mid-October 2019, when the stations were dismantled and removed. There are two meteorological monitoring stations at the site: one north of the contamination area and one to the south (Figure C-7). The channel-flow and sediment sampling equipment are located in a channel close to the south meteorological station. The two Plutonium Valley stations included a full suite of meteorological equipment (wind speed, wind direction, air temperature, air relative humidity, barometric pressure, soil temperature, soil volumetric water content, and solar radiation) and an aerosol/dust-monitoring instrument. Per an EM NV decision, no samplers for suspended dust were deployed at the site.

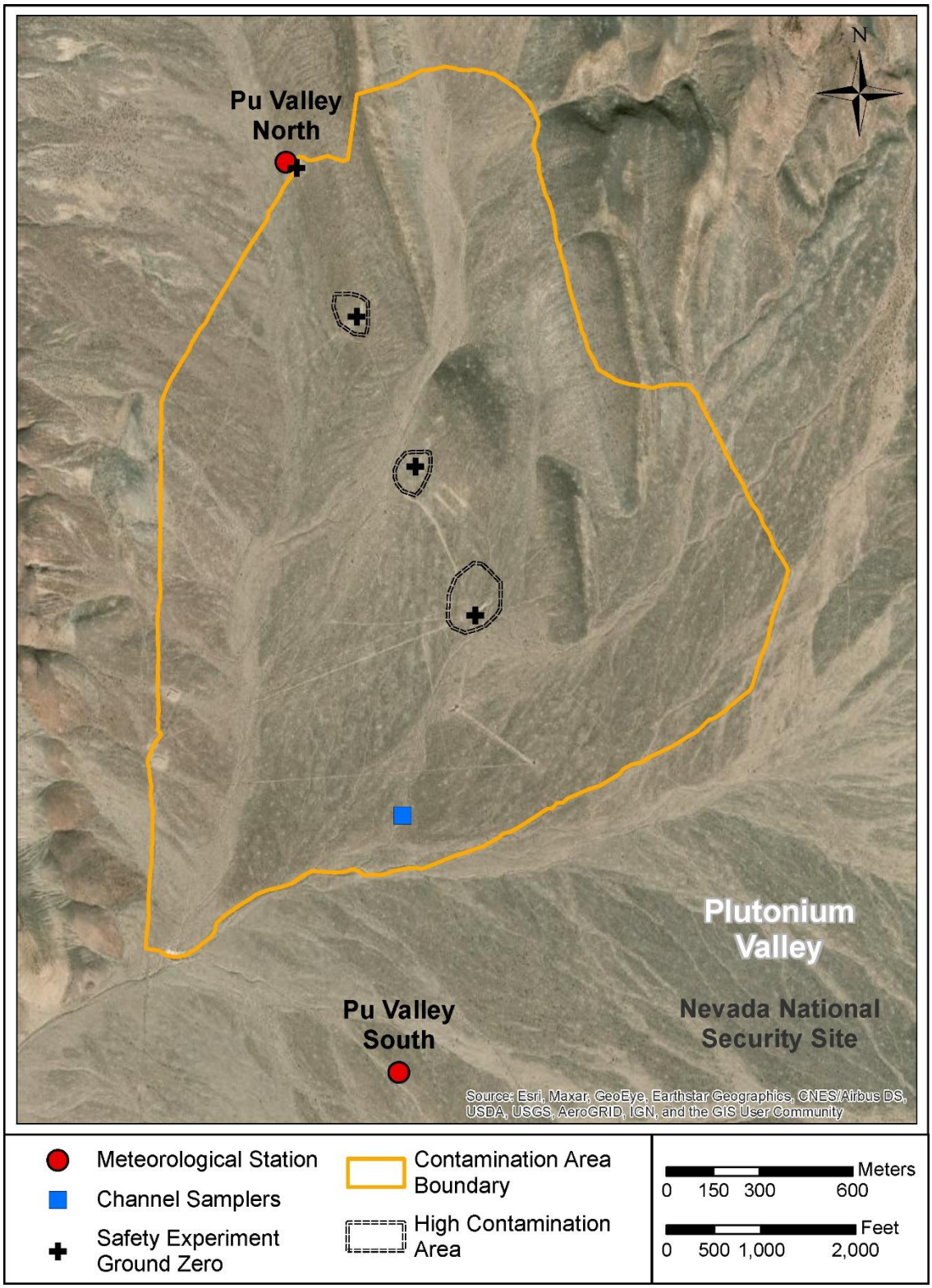

Figure C-7. Locations of the Plutonium Valley north and south meteorological stations relative to the contamination and high contamination areas.

Wind Speed and Direction

Wind rose graphs (explained in the Smoky Site "Wind Speed and Direction" section) summarize the direction and speed of winds at the two monitoring stations (Figure C-8 for the north station and Figure C-9 for the south station). Overall, winds from the northwest and south are most frequent, and the frequency of winds from the east and west is very low. Over 97 percent of sustained winds greater than 15 mph during the first, second, and fourth quarters of the year blow from the north, northwest, and south, whereas the frequency is over 90 percent during the third quarter of the year.

Seasonally, the winds from the north and northwest are more frequent during the first and fourth quarter of the year, whereas winds from the south are more frequent during the second and third quarter (Figures C-8 and C-9). Sustained winds over 15 mph out of the south are most frequent during the second and third quarter and least frequent during the fourth quarter (Figures C-10 and C-11). Sustained winds over 15 mph are most frequent in April and least frequent in August (Figure C-12). Approximately 70 percent of winds greater than 25 mph blow in just two months of the year, March and April (Figure C-13). Overall, sustained winds greater than 15 mph blow for only five percent of the time during the year (Figure C-14).

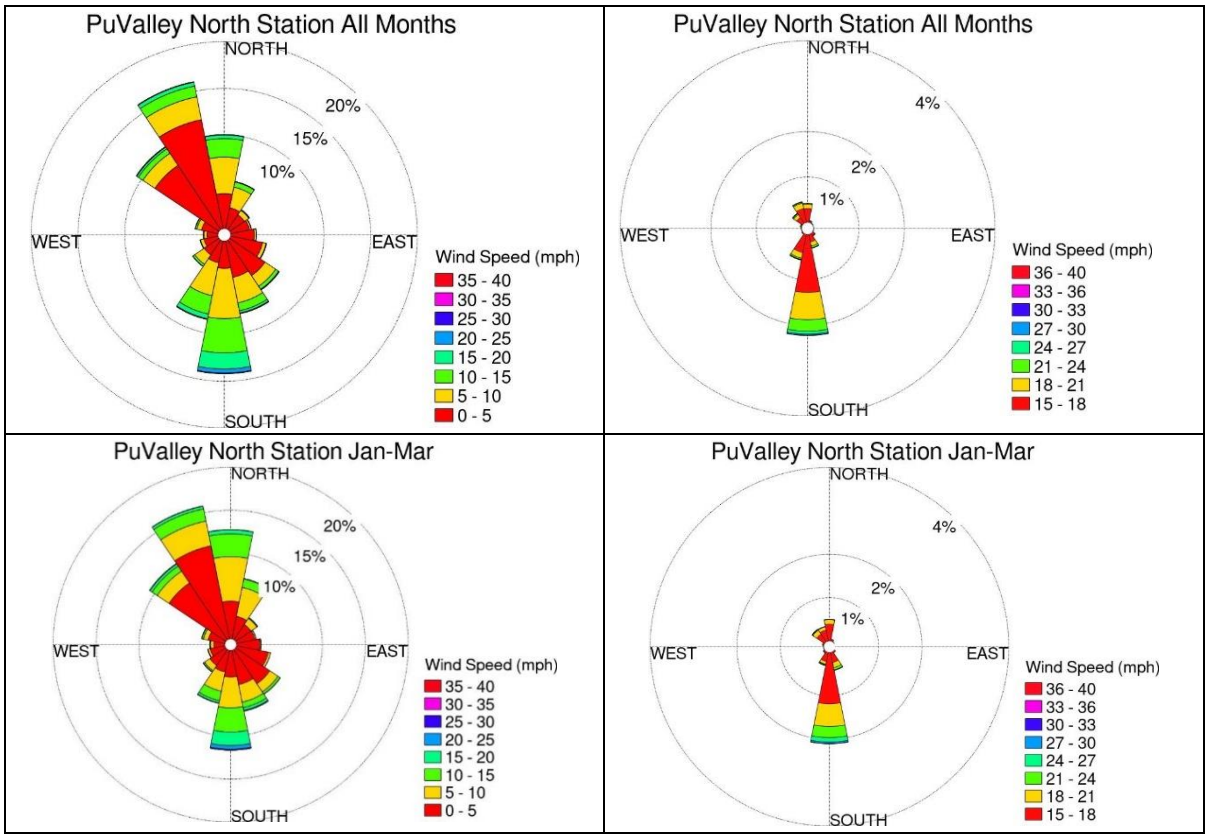

Figure C-8. Wind roses for the Plutonium Valley north station displaying data from 2015 to 2019. The top row shows data for all months and the lower rows show quarterly data. The left column includes all winds and the right column presents only winds greater than 15 mph.

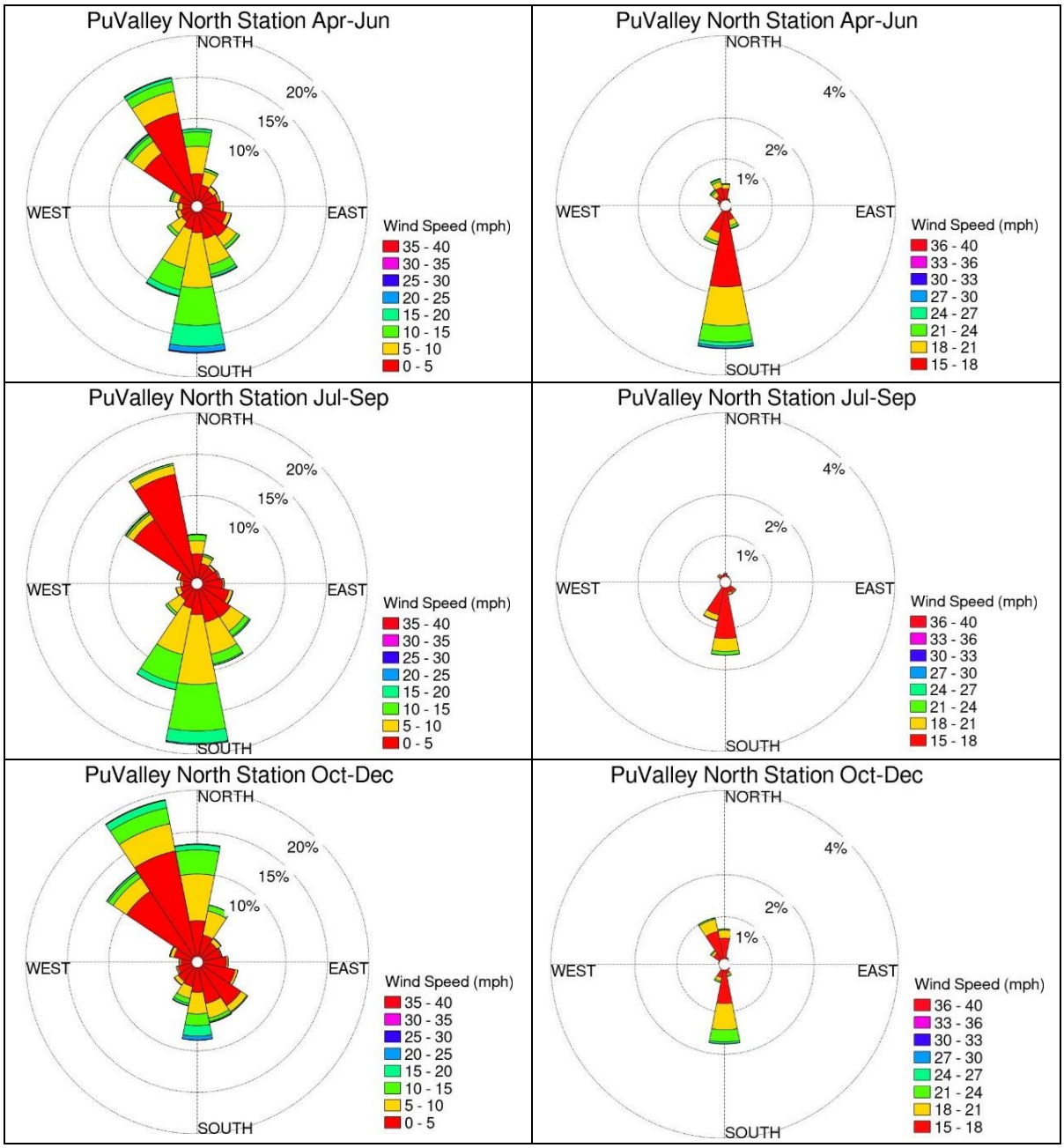

Figure C-8. Wind roses for the Plutonium Valley north station displaying data from 2015 to 2019. The top row shows data for all months and the lower rows show quarterly data. The left column includes all winds and the right column presents only winds greater than 15 mph (continued).

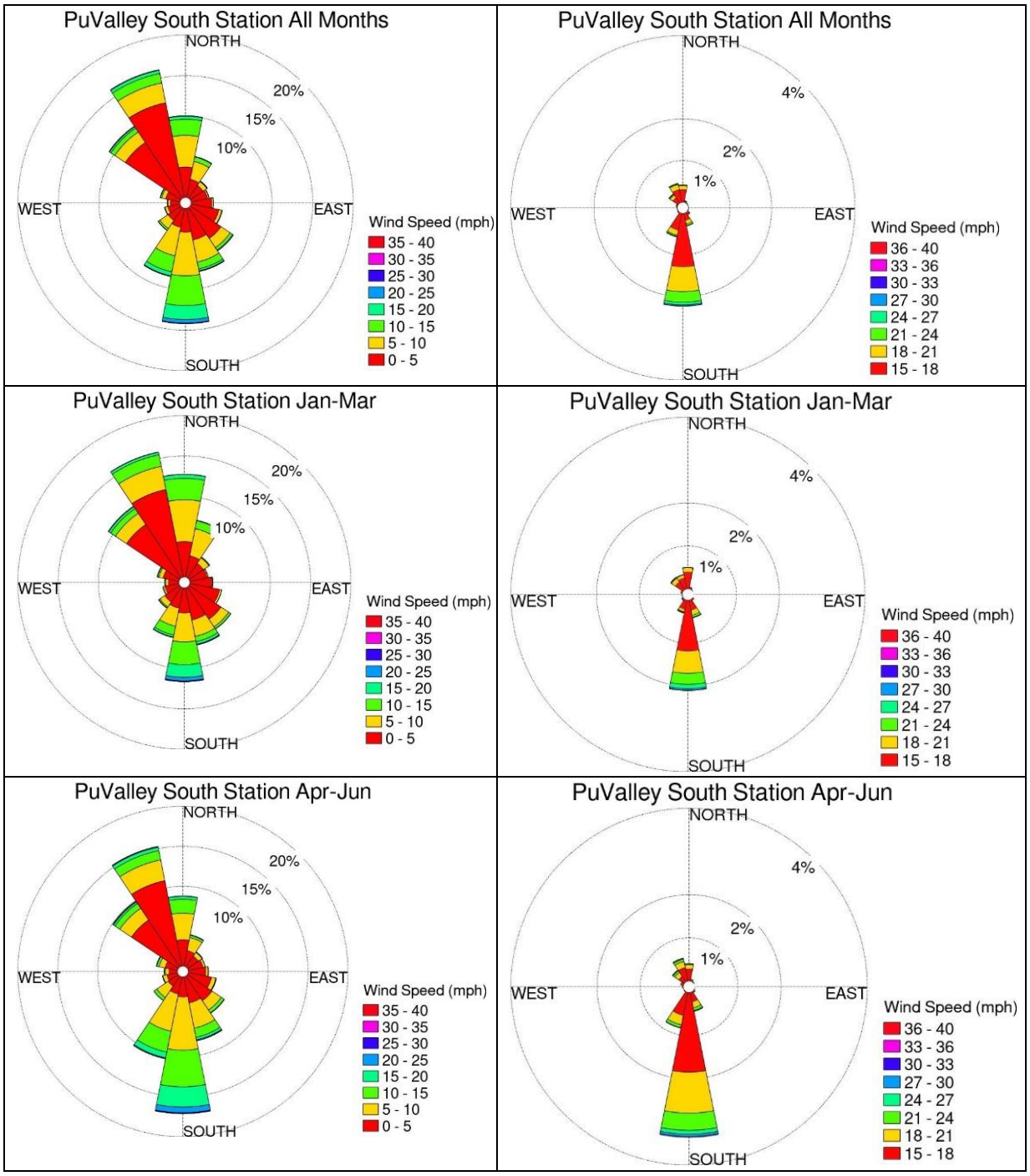

Figure C-9. Wind roses for the Plutonium Valley south station displaying data from 2015 to 2019. The top row shows data for all months and the lower rows show quarterly data. The left column includes all winds and the right column presents only winds greater than 15 mph.

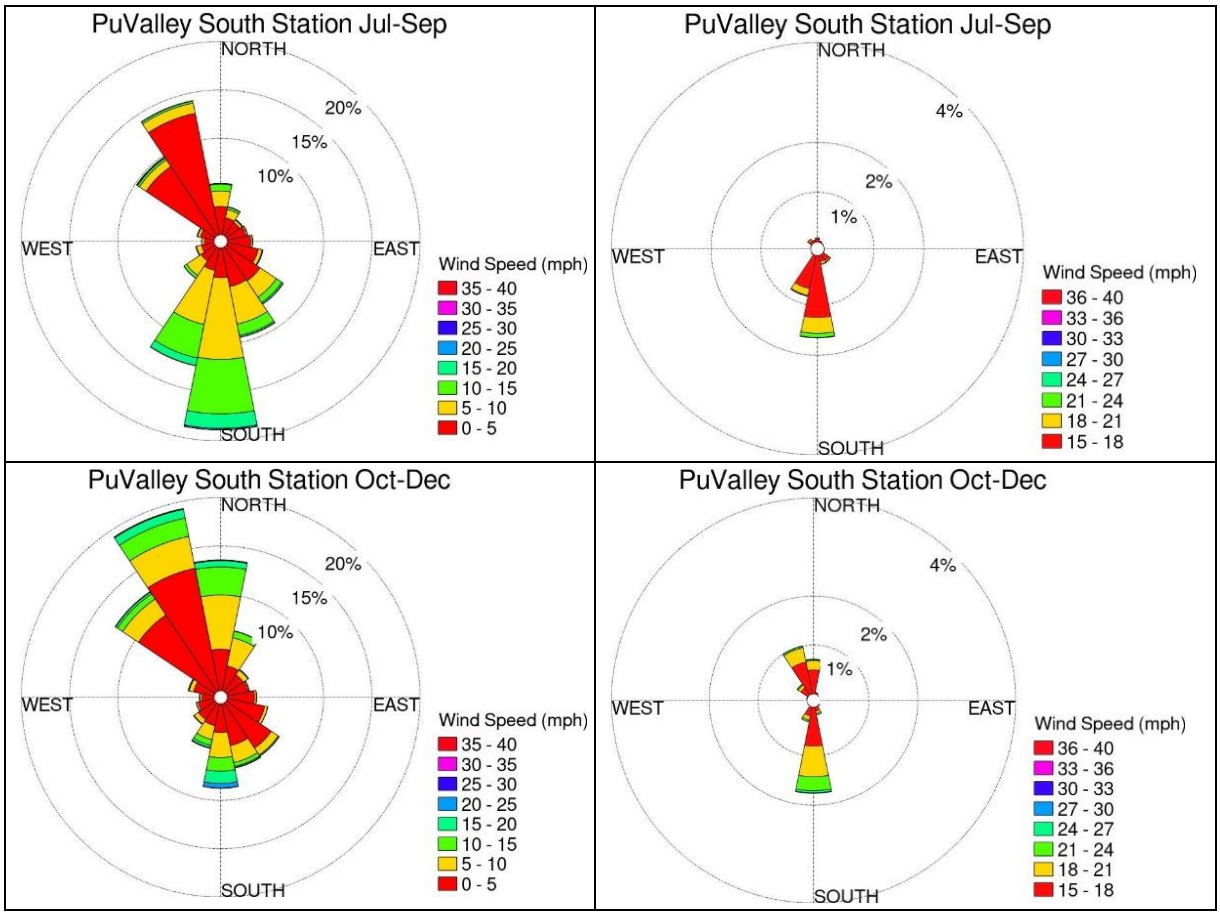

Figure C-9. Wind roses for the Plutonium Valley south station displaying data from 2015 to 2019. The top row shows data for all months and the lower rows show quarterly data. The left column includes all winds and the right column presents only winds greater than 15 mph (continued).

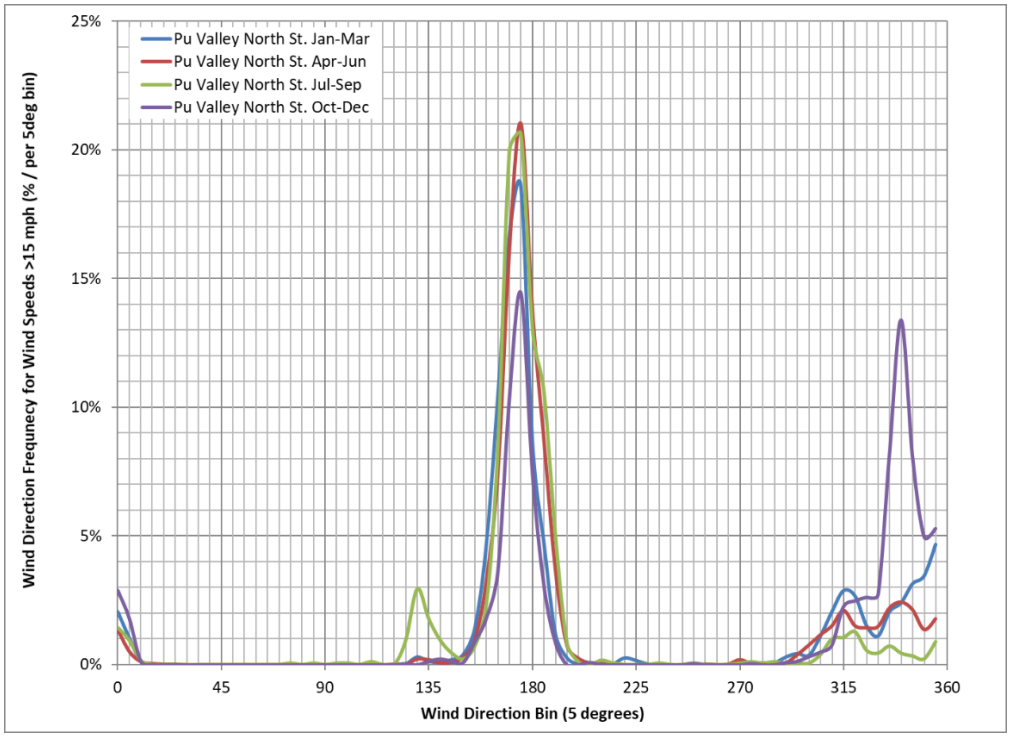

Figure C-10. Wind direction frequency for each three-month period at the Plutonium Valley north station for 2015 to 2019.

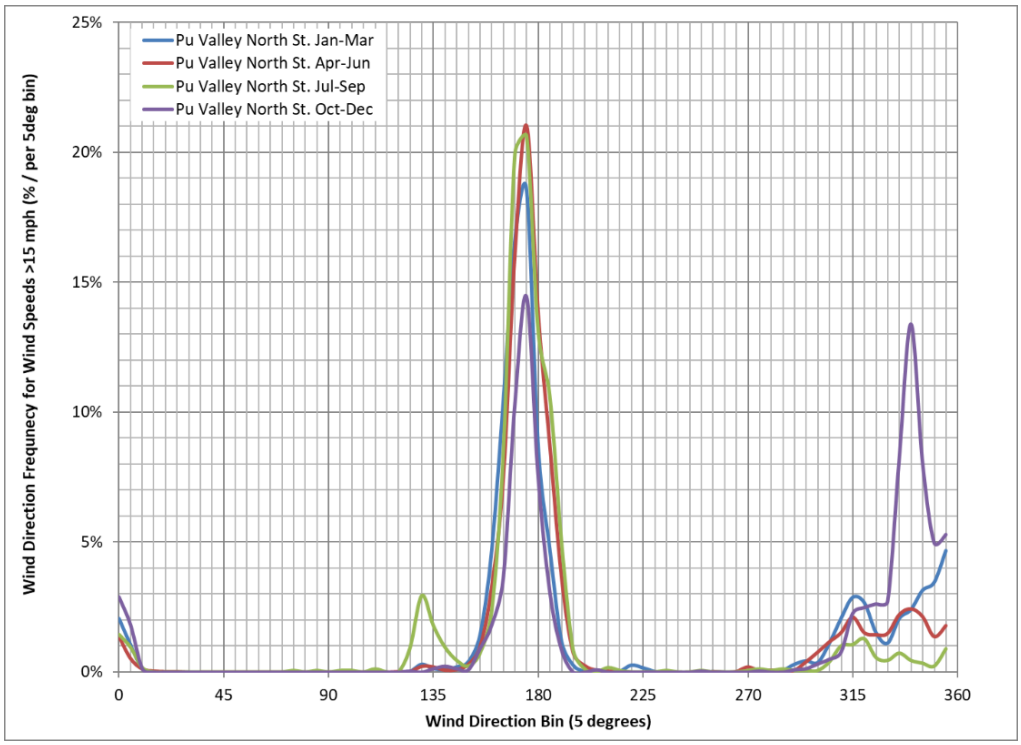

Figure C-11. Wind direction frequency for each three-month period at the Plutonium Valley south station for 2015 to 2019.

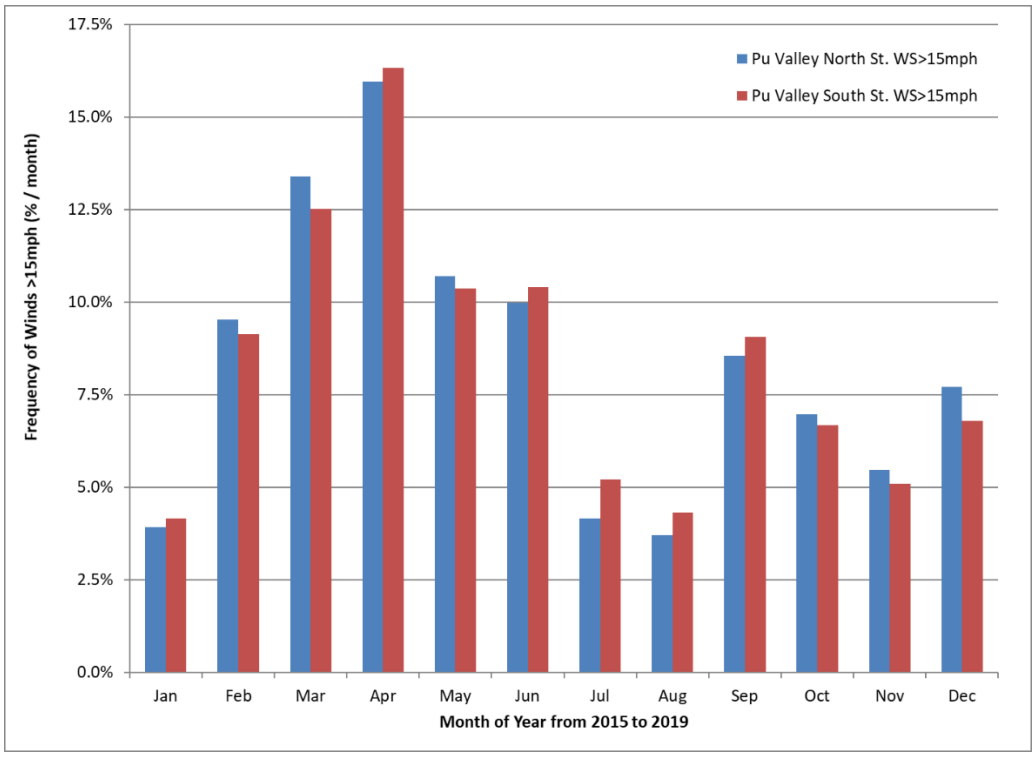

Figure C-12. Monthly wind frequency distribution of winds over 15 mph from 2015 to 2019.

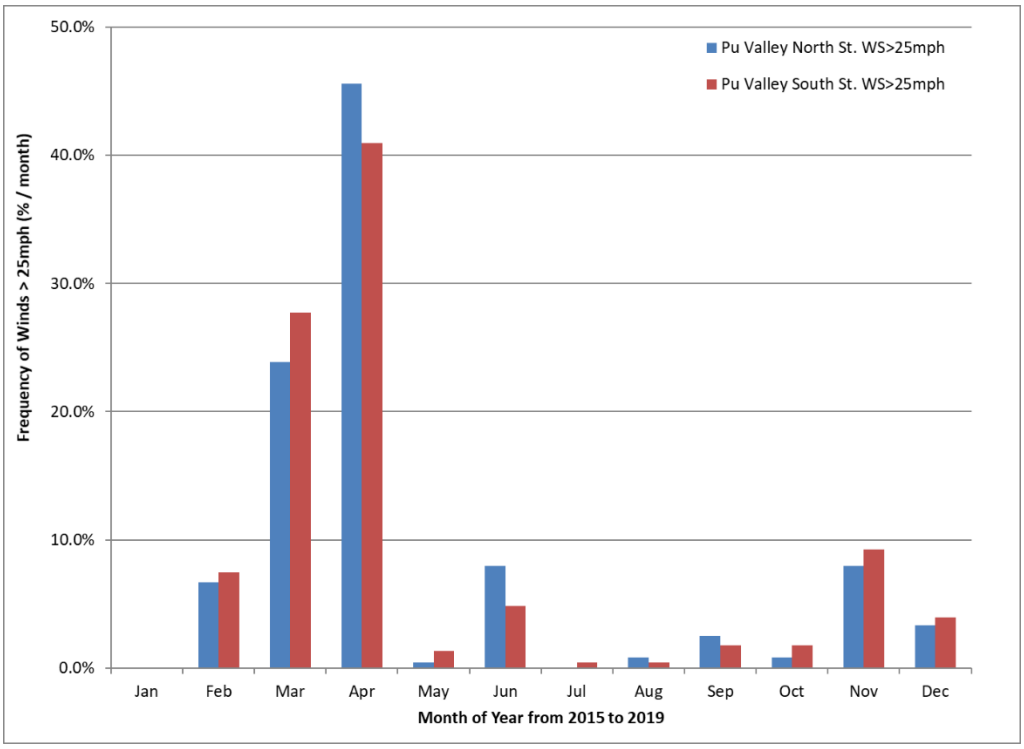

Figure C-13. Monthly wind frequency distribution of winds over 25 mph from 2015 to 2019.

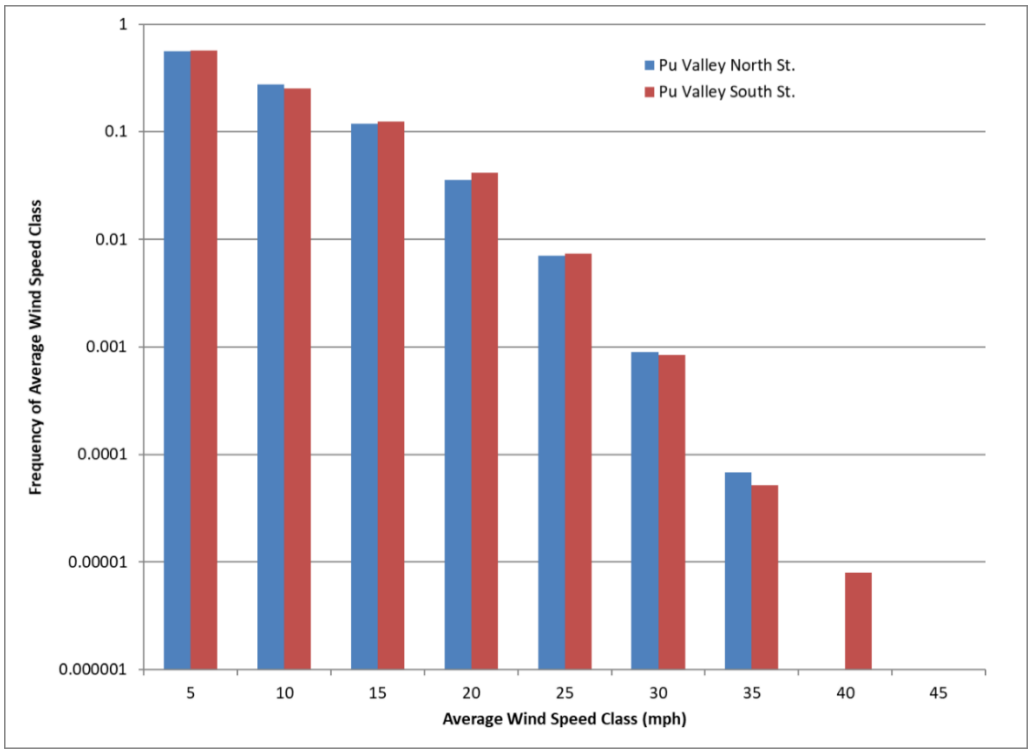

Figure C-14. Wind frequency distribution by 5 mph wind speed class for the Plutonium Valley stations for 2015 to 2019.

Dust Transport

The average PM_{10} measured between 2015 and 2019 at the Plutonium Valley stations is nearly constant at a concentration of 10 µg/m^3 for winds below 15 mph (Figure C-15). The stable PM_{10} concentration for winds below 15 mph indicates that winds are not strong enough to suspend an appreciable amount of local dust. As winds increase over 15 mph, an exponential increase in the PM_{10} concentration is observed up to a wind speed of 30 mph. The PM_{10} values at the north and south stations are similar for winds up to 30 mph, but over 30 mph, the PM_{10} concentration at the north station decreases while the concentration at the south station continues to increase but exhibits an inflection in slope. The behavior observed at both stations is consistent with what occurs when there are supply limitations of either suspendable dust or saltation-sized particles, and what is expected for desert landscapes that are not sand dunes (where the supply is essentially unlimited). However, it is important to note that wind speeds over 30 mph are very infrequent (a total of approximately three hours split between multiple events over the five-year period considered here), so this interpretation of the observed wind and PM_{10} is subject to uncertainty because of the relatively sparse data.

The PM_{10} concentration is lowest during the first quarter of the year for wind speeds below 35 mph (Figures C-16 and C-17). The first quarter is characterized by lower temperatures, lower evaporation rates, and higher precipitation, which all lead to higher relative humidity (RH) and soil water content. The first quarter of the year has the highest relative humidity (Figure C-18). Higher air humidity and higher soil moisture bind soil

particles and serve to reduce windblown dust emissions. The PM_{10} concentrations for winds up to 25 mph are highest during the second and third quarter of the year when relative humidity is at its lowest value. The increase in RH during the third quarter for winds above 20 mph (Figure C-18) reflects storm outflows during monsoonal rain events. Grouping the wind speed and PM_{10} relationships by RH supports the overall relationship of lower average PM_{10} concentrations for a given wind speed at higher relative humidity values (Figures C-19 and C-20).

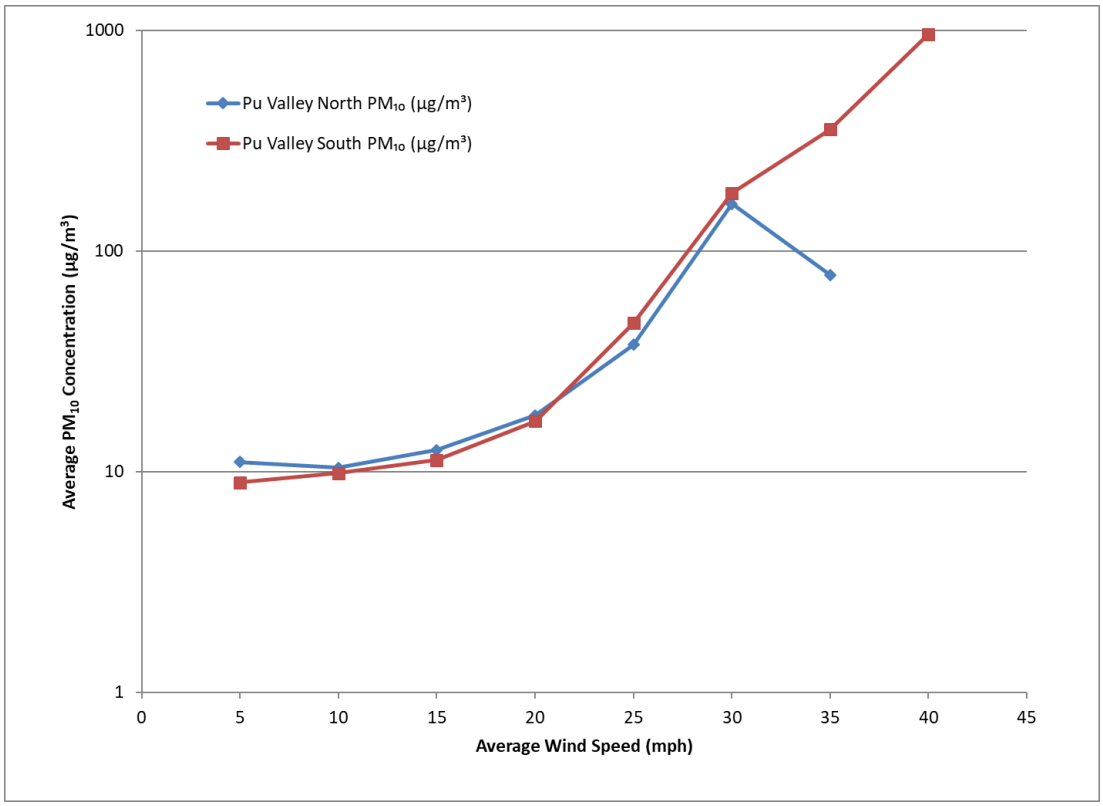

Figure C-15. PM_{10} versus the average wind speed for the Plutonium Valley north and south monitoring stations for 2015 to 2019.

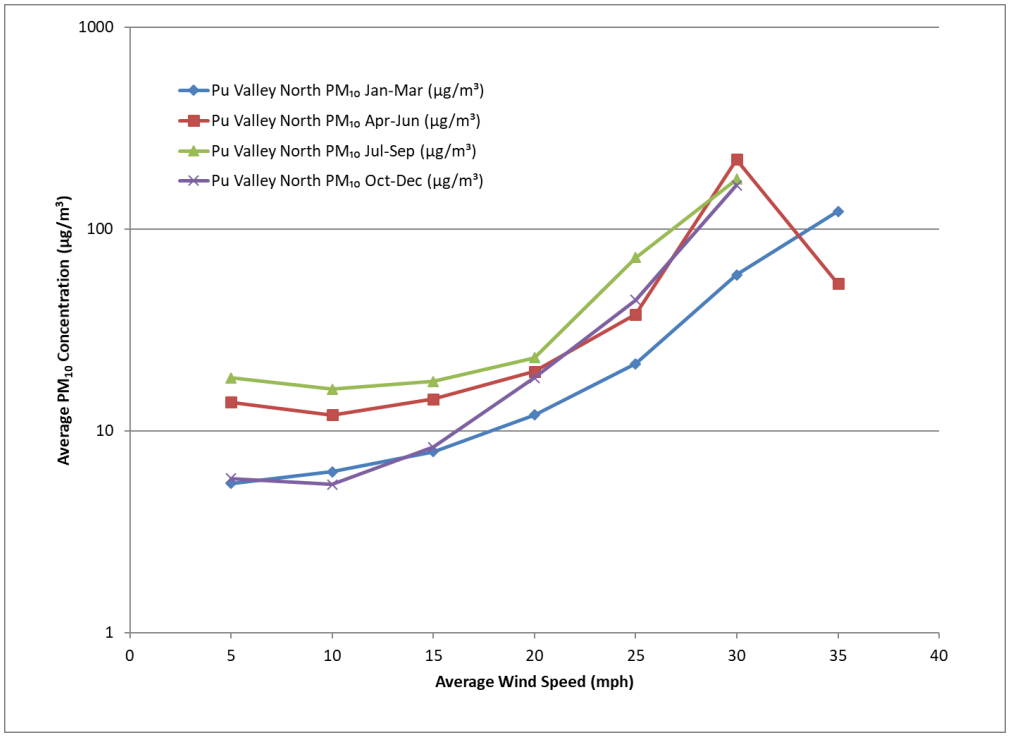

Figure C-16. Quarterly PM_{10} versus the average wind speed trend for the Plutonium Valley north monitoring station for 2015 to 2019.

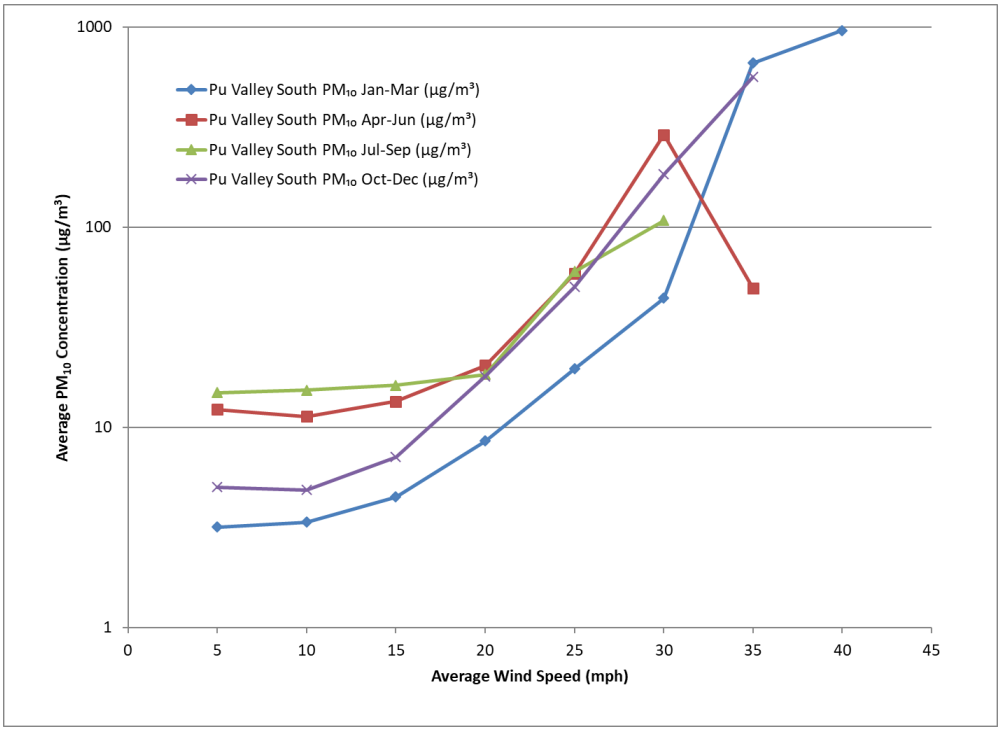

Figure C-17. Quarterly PM_{10} versus the average wind speed trend for the Plutonium Valley south monitoring station for 2015 to 2019.

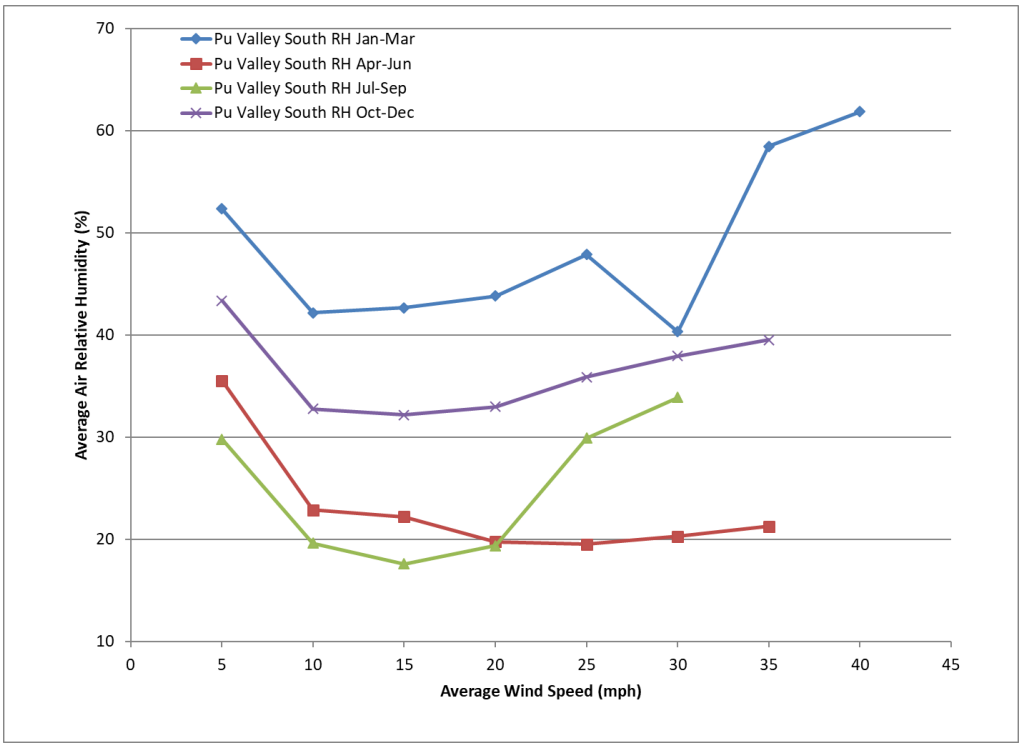

Figure C-18. Quarterly relative humidity (RH) versus the average wind speed for the Plutonium Valley south monitoring station for 2015 to 2019.

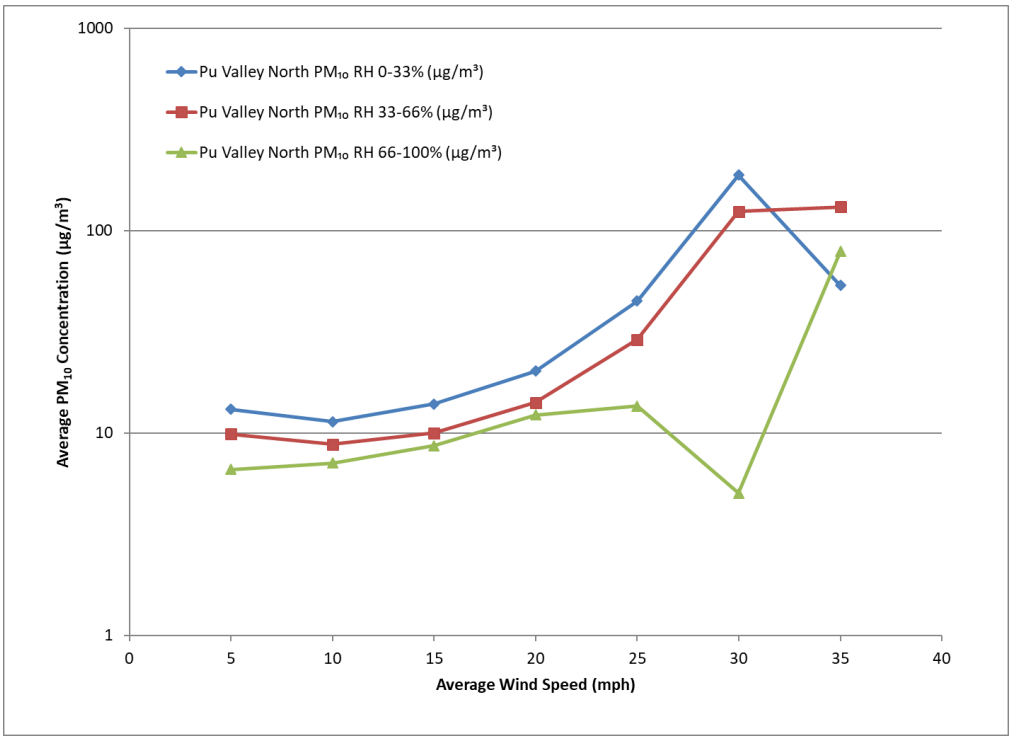

Figure C-19. PM_{10} relative to average wind speed, grouped by relative humidity (RH), for the Plutonium Valley north monitoring station for 2015 to 2019.

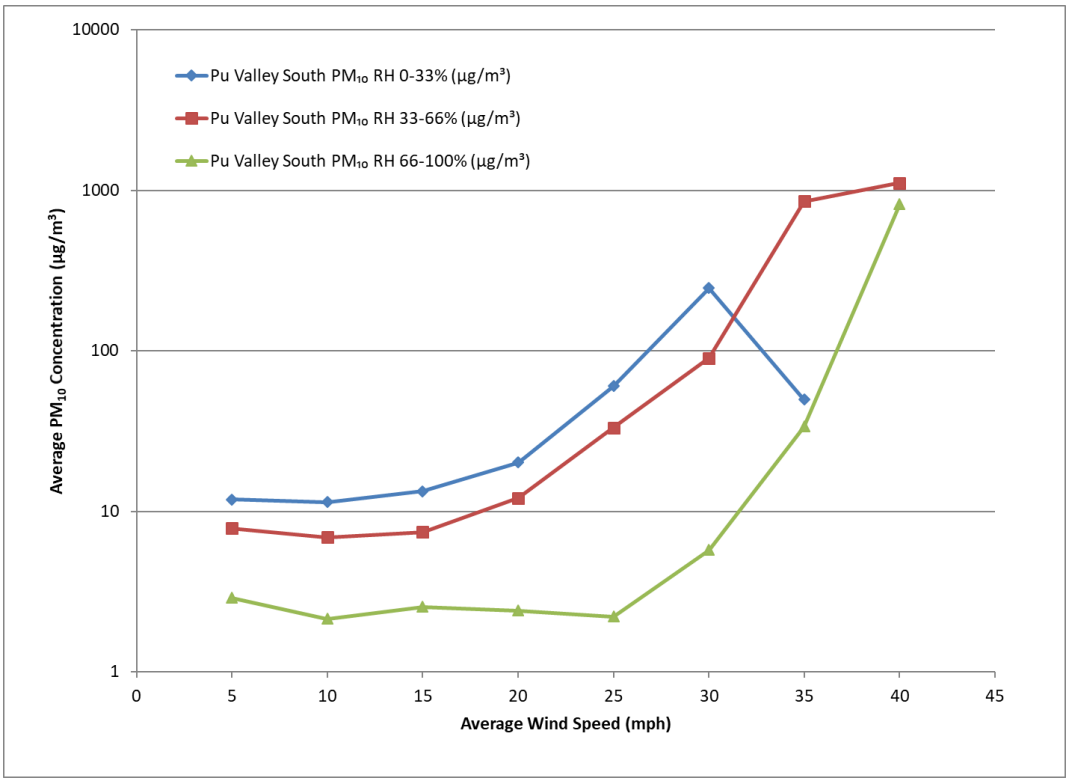

Figure C-20. PM_{10} relative to average wind speed, grouped by relative humidity (RH), for the Plutonium Valley south monitoring station for 2015 to 2019.

Project 57

The data summarized for Project 57 were collected from Stations 503 and 504 from 2015 through 2019. These stations were established at the end of 2014, having been moved from the previous locations (denoted as 501 and 502) based on monitoring observations to better position them downwind from the contamination area during the prevalent northwest and south winds (Figure C-21). Station 503 was north of the contamination area, and therefore downwind during winds from the south. Station 504 was south of the contamination area and downwind during north winds. The stations included a full suite of meteorological instruments and real-time instrumentation to record dust concentration and sand transport. A continuous air sampler was operated and filter samples collected every two weeks. Filter collections provided samples of loaded particulate matter on filters that were analyzed for the presence of radioactive isotopes.

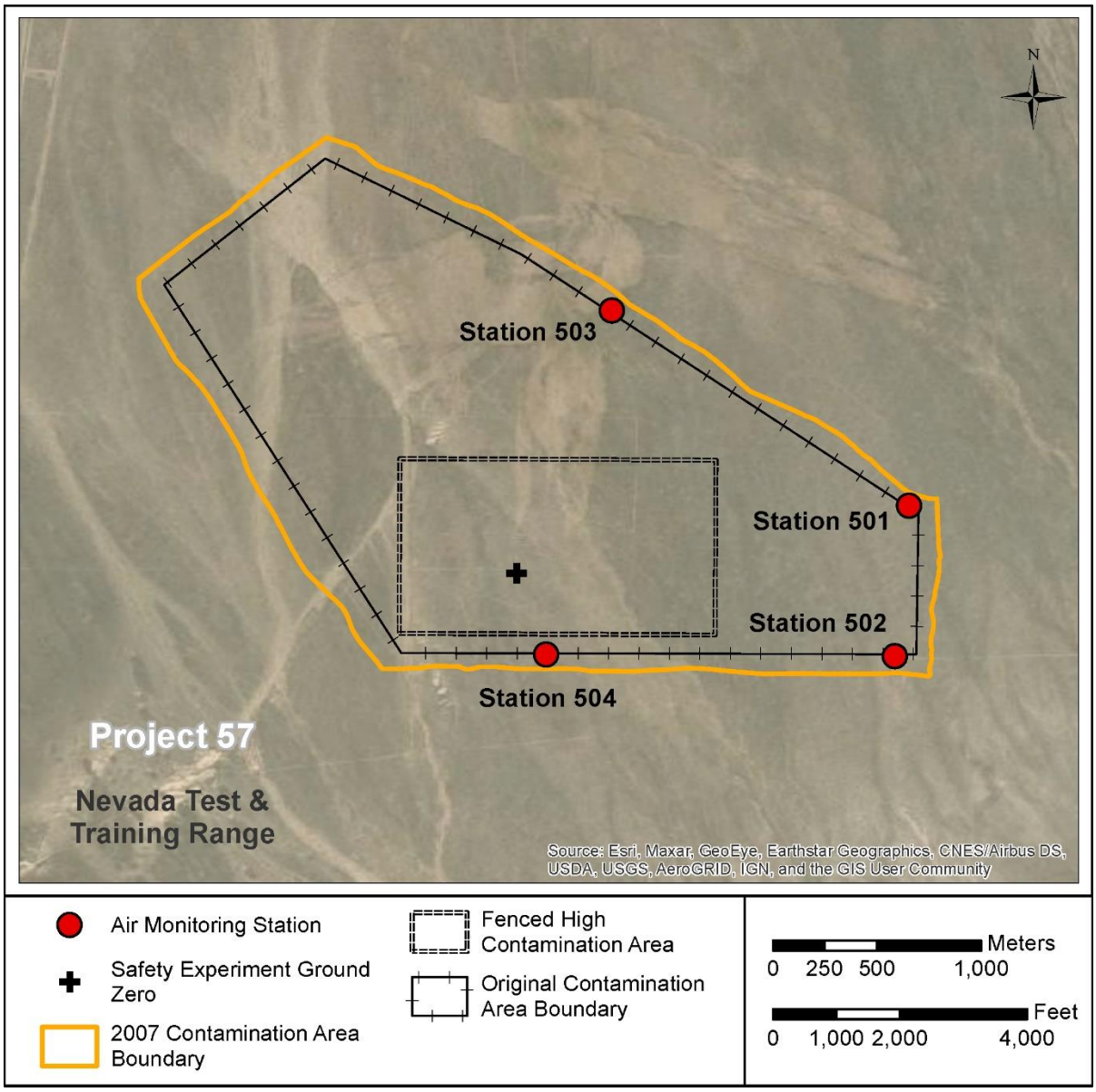

Figure C-21. Location of Project 57 monitoring stations relative to the contamination and high contamination areas.

Wind Speed and Direction

Prevailing wind directions are from the north and south at Project 57 (Figures C-22 and C-23). These directions are also responsible for over 90 percent of winds greater than 15 mph. The wind direction frequency changes with the seasons. The majority of winds greater than 15 mph blow from the north and northwest between October and March, whereas the majority blow from the south between April and September. The wind direction frequency is similar for the two stations (Figures C-24 and C-25).

High winds are most frequent between December and April, with the maximum occurrence in April (Figures C-26 and C-27). The lowest frequency of winds over 15 mph was observed in July and August. The high winds that drive dust and sand transport are infrequent and short in duration, with winds greater than 15 mph occurring for approximately 10 percent of the year and winds greater than 25 mph occurring for less than 1 percent of the year (Figure C-28).

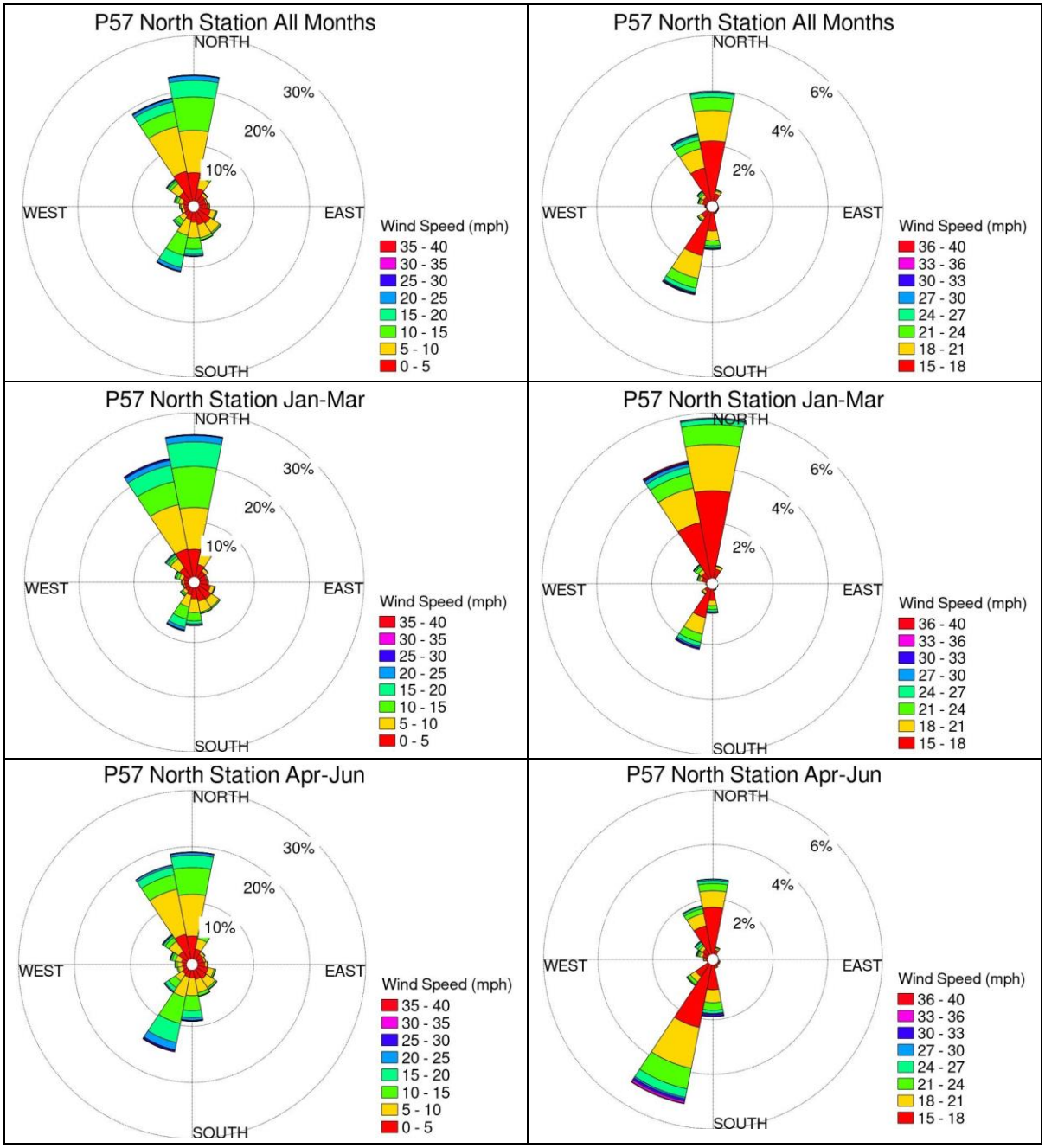

Figure C-22. Wind roses for Station 503, north of Project 57, displaying data from 2015 to 2019 for all months (top row) and quarterly (lower rows). The left column shows data for all winds and the right column shows data for winds in greater than 15 mph.

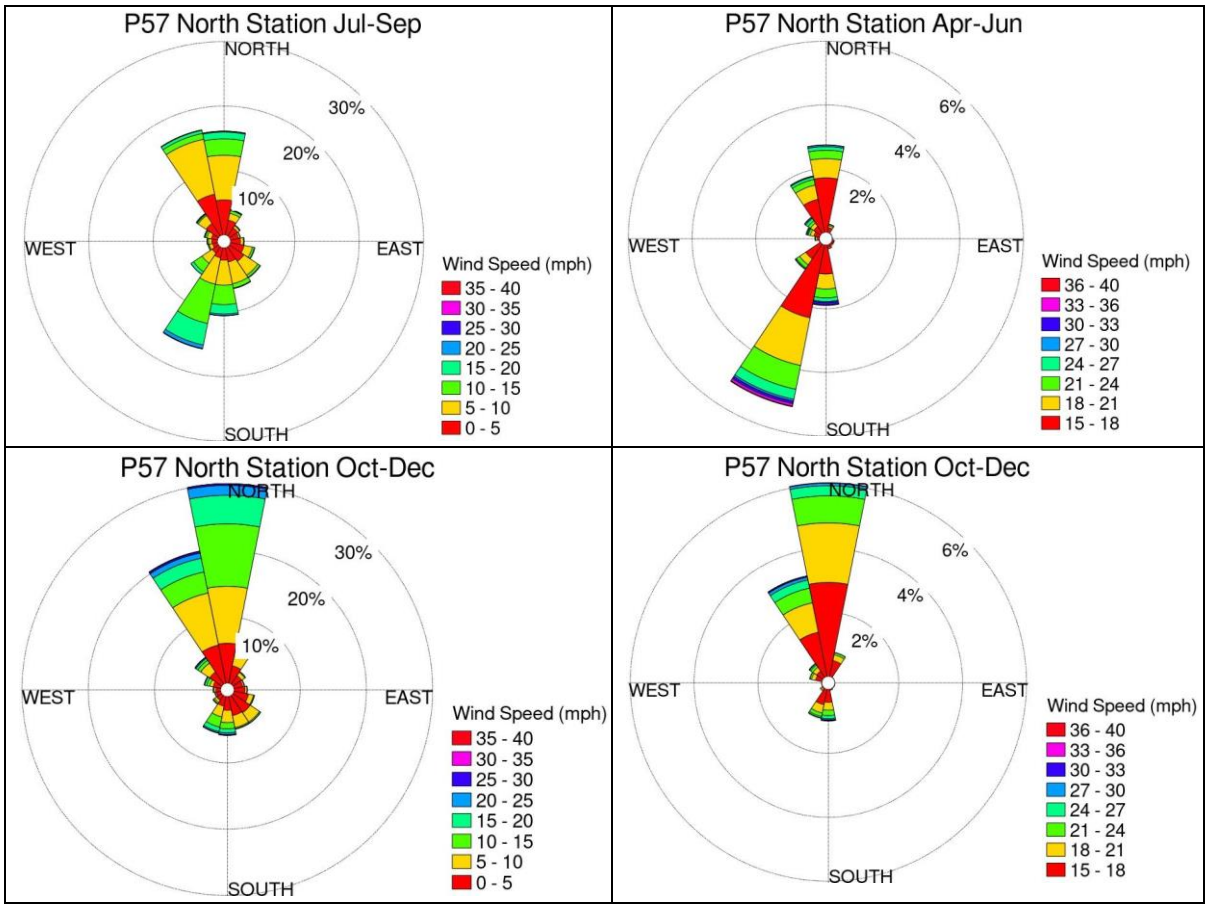

Figure C-22. Wind roses for Station 503, north of Project 57, displaying data from 2015 to 2019 for all months (top row) and quarterly (lower rows). The left column shows data for all winds and the right column shows data for winds in greater than 15 mph (continued).

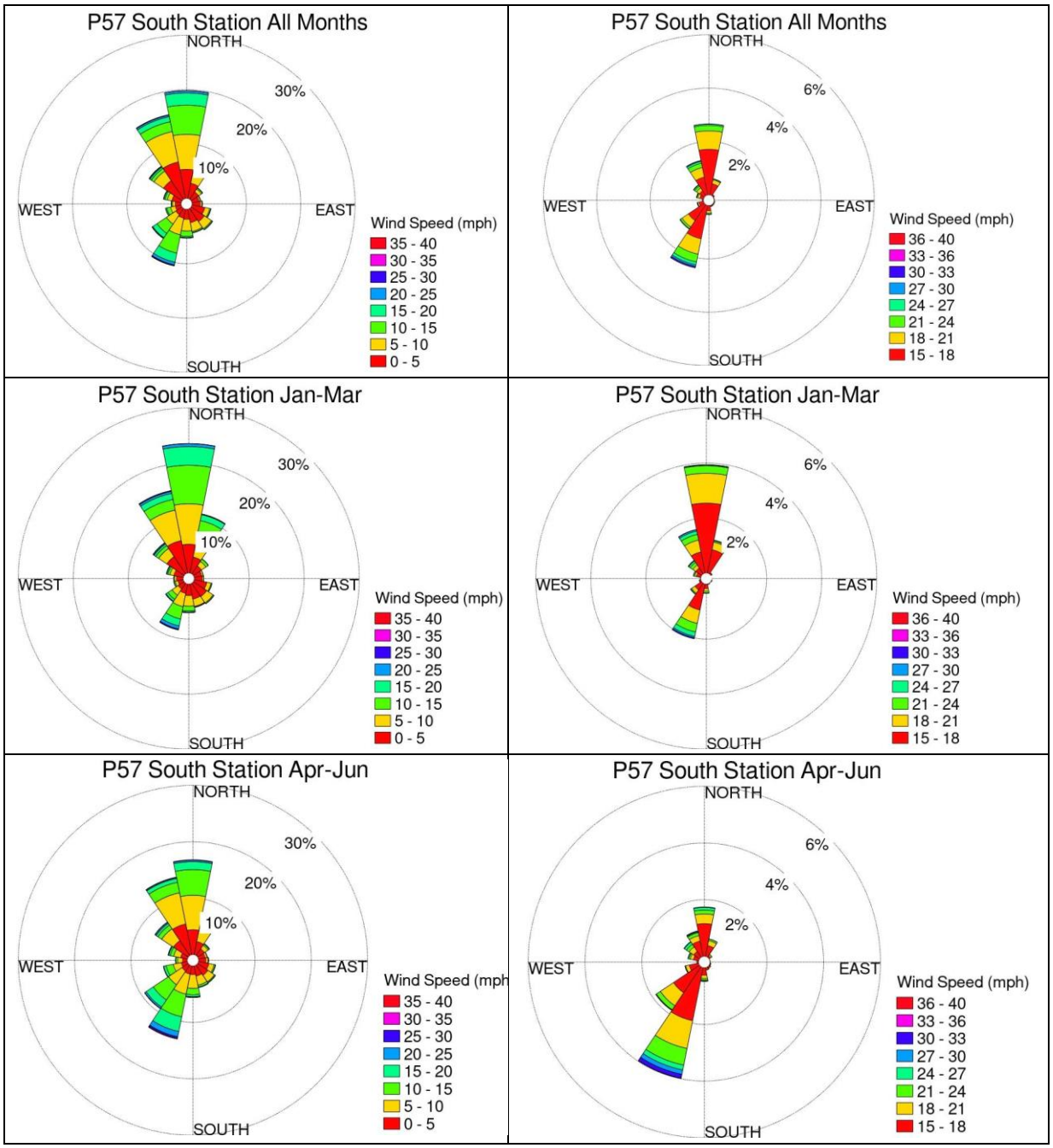

Figure C-23. Wind roses for Station 504, south of Project 57, displaying data from 2015 to 2019 for all months (top row) and quarterly (lower rows). The left column shows data for all winds and the right column shows data for winds in greater than 15 mph.

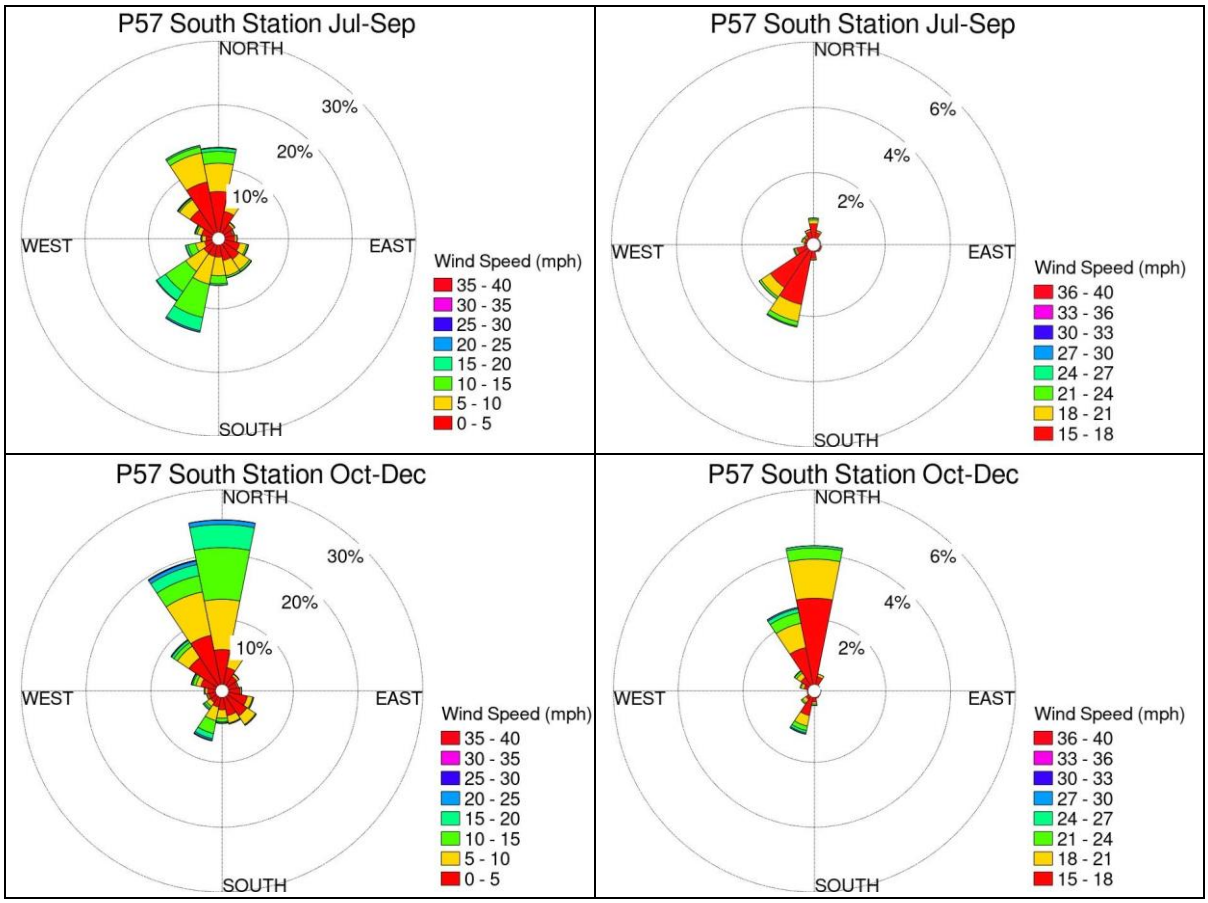

Figure C-23. Wind roses for Station 504, south of Project 57, displaying data from 2015 to 2019 for all months (top row) and quarterly (lower rows). The left column shows data for all winds and the right column shows data for winds in greater than 15 mph (continued).

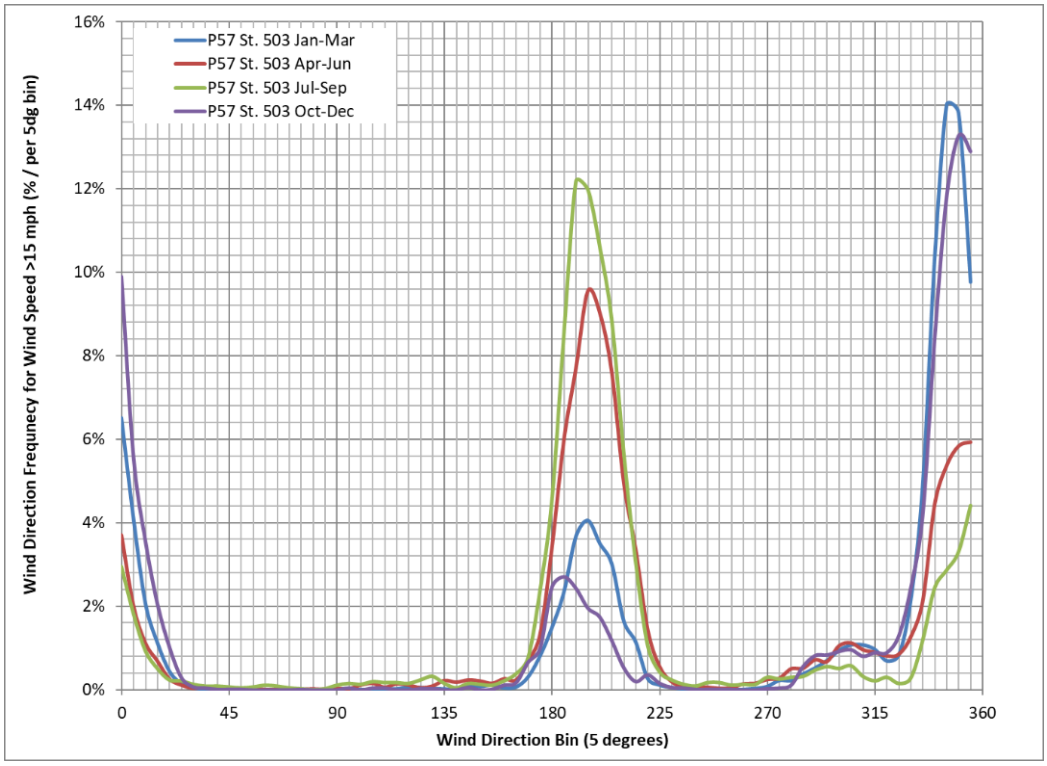

Figure C-24. Wind direction frequency for each three-month period for Station 503 for 2015 to 2019.

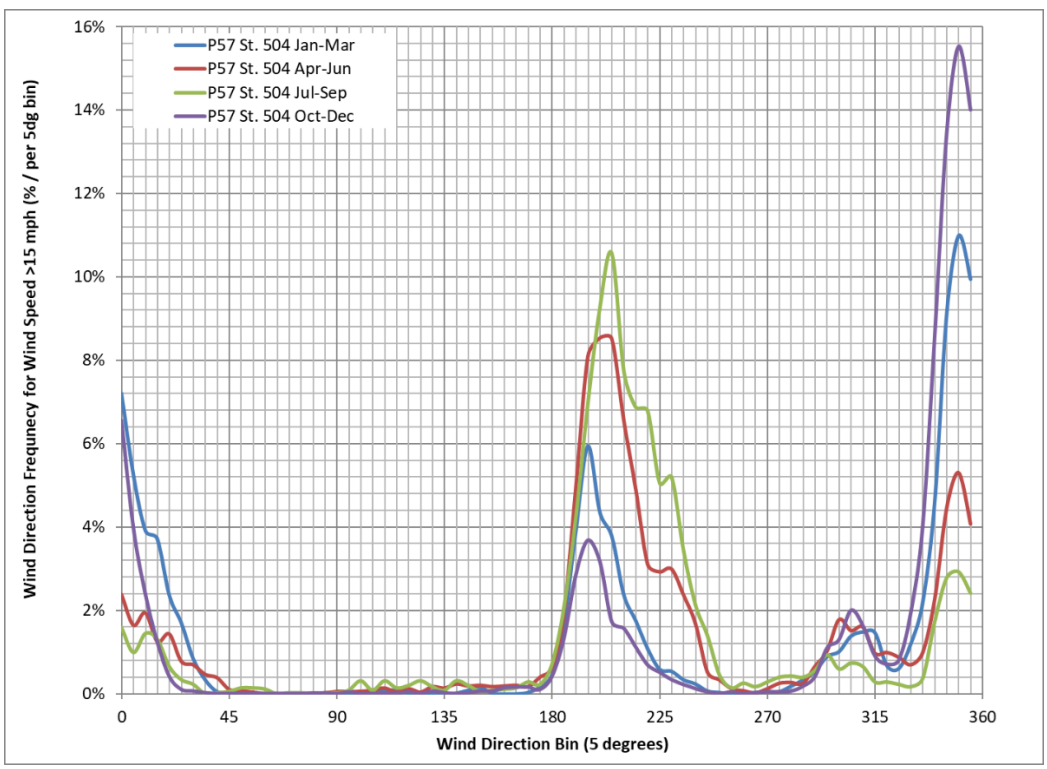

Figure C-25. Wind direction frequency for each three-month period for Station 504 for 2015 to 2019.

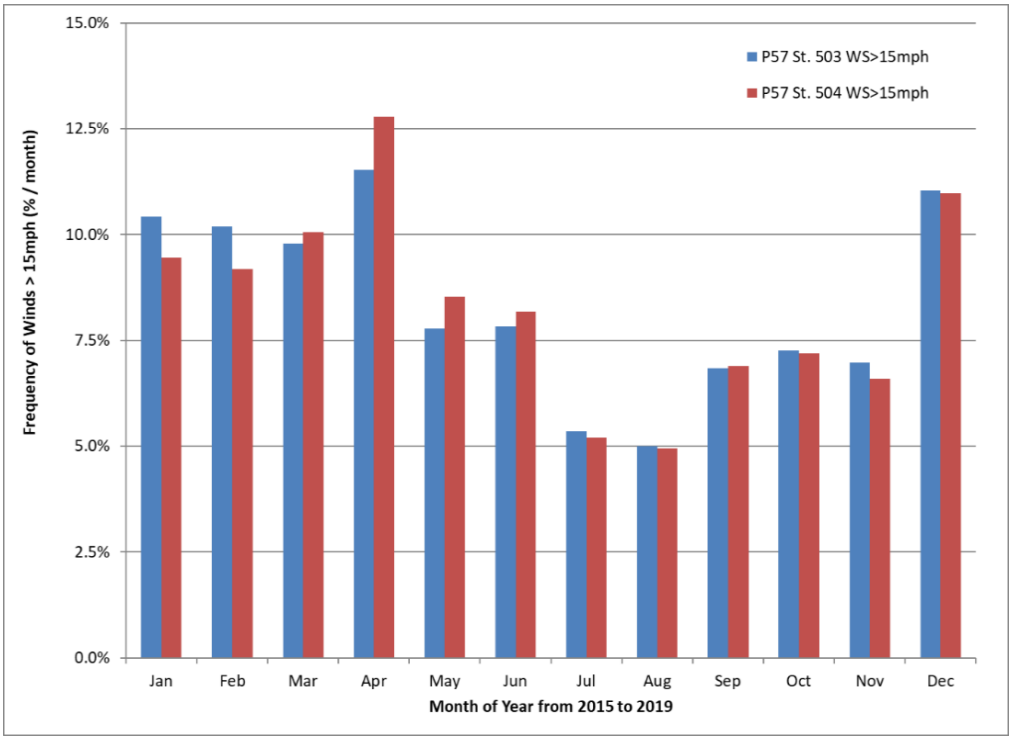

Figure C-26. Monthly wind frequency distribution of winds over 15 mph from 2015 to 2019 for both Project 57 stations.

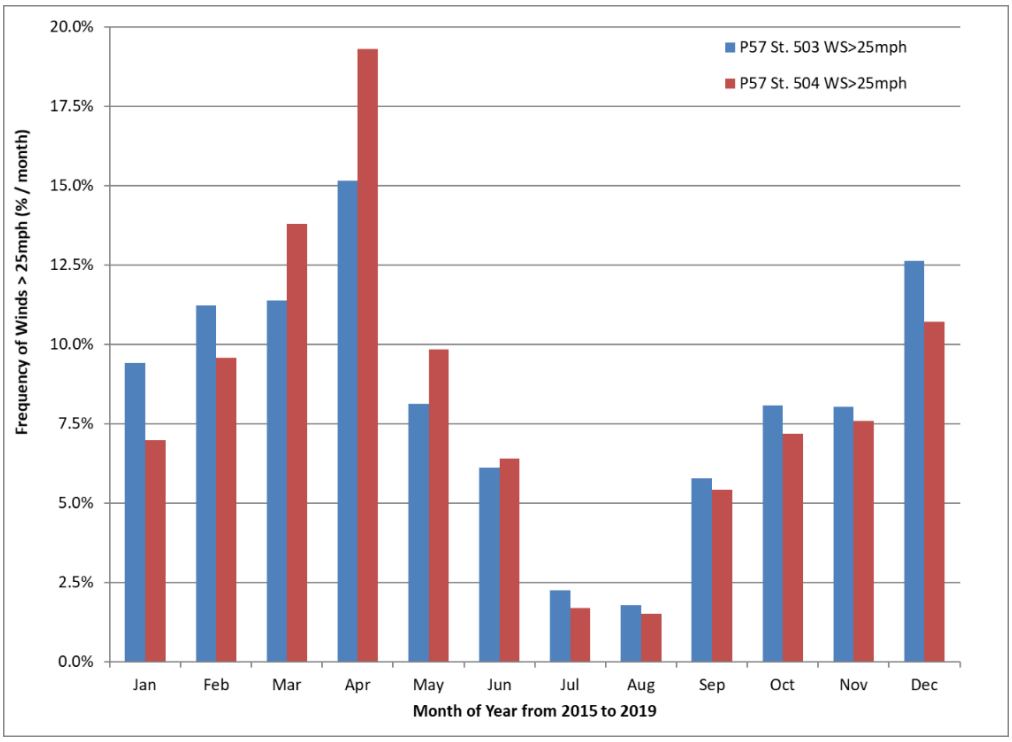

Figure C-27. Monthly wind frequency distribution of winds over 25 mph from 2015 to 2019 for both Project 57 stations.

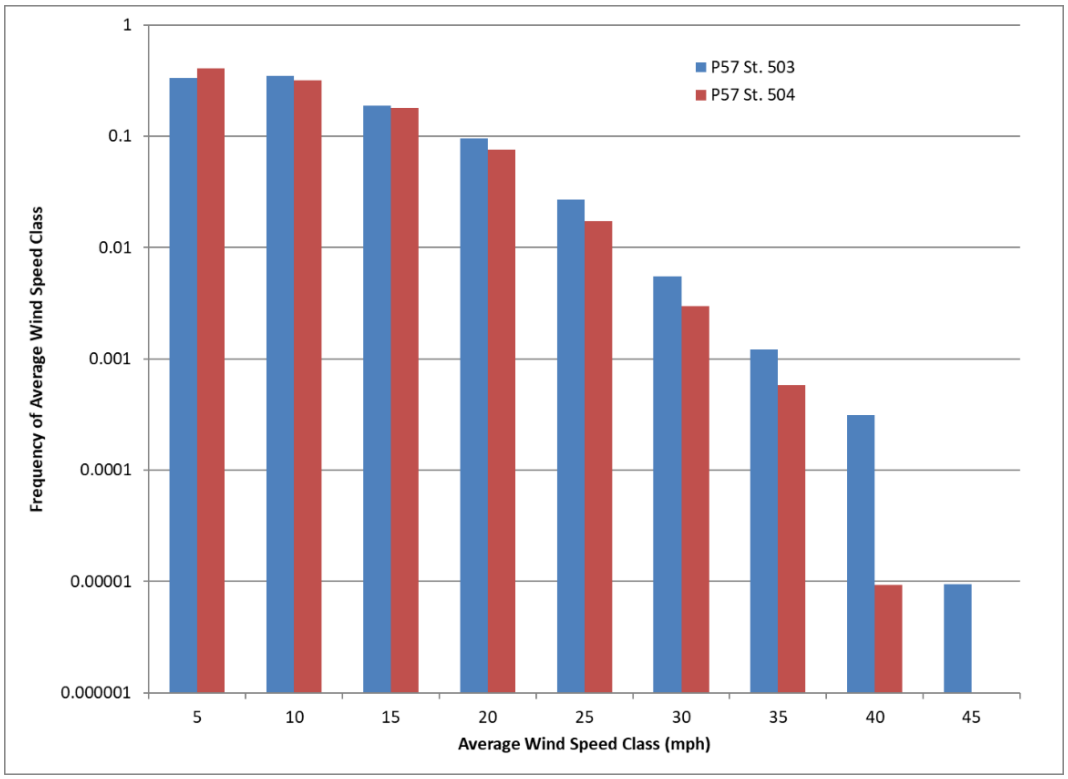

Figure C-28. Wind frequency distribution by 5 mph wind speed class for 2015 to 2019 for both Project 57 stations.

Dust Transport

The average PM_{10} concentration measured at the Project 57 stations between 2015 and 2019 is approximately 12.5 µg/m^3 for winds below 15 mph (Figure C-29). This dust load is close to the background PM_{10} concentration as inferred from DRI monitoring of Soils Activity sites throughout southern and central Nevada. The stable PM_{10} concentration for winds below 15 mph suggests that these winds are not strong enough to suspend local dust. An approximate exponential increase in the PM_{10} concentration is observed as winds increase between 15 mph and 30 mph. Sustained winds over 35 mph carry a lower PM_{10} concentration compared with the 30 mph winds, which is a possible indication of a dust supply limitation. Although high wind periods are infrequent and relatively brief, those conditions are important for local dust movement.

The PM_{10} is highest during the July to September and April to June quarters (Figures C-30 and C-31). Although the frequency of winds over 15 mph is the lowest during July to September (Figure C-26), dust transport is affected by air relative humidity, a parameter that is also an indicator of soil moisture. The relative humidity is low during the summer months (Figure C-32), resulting in dry soil conditions that are more prone to dust generation. The influence of relative humidity on PM_{10} is observed by the one-order-of-magnitude decrease of PM_{10} when the relative humidity is greater than 66 percent, compared with times when the relative humidity is lower than 33 percent (Figures C-33 and C-34).

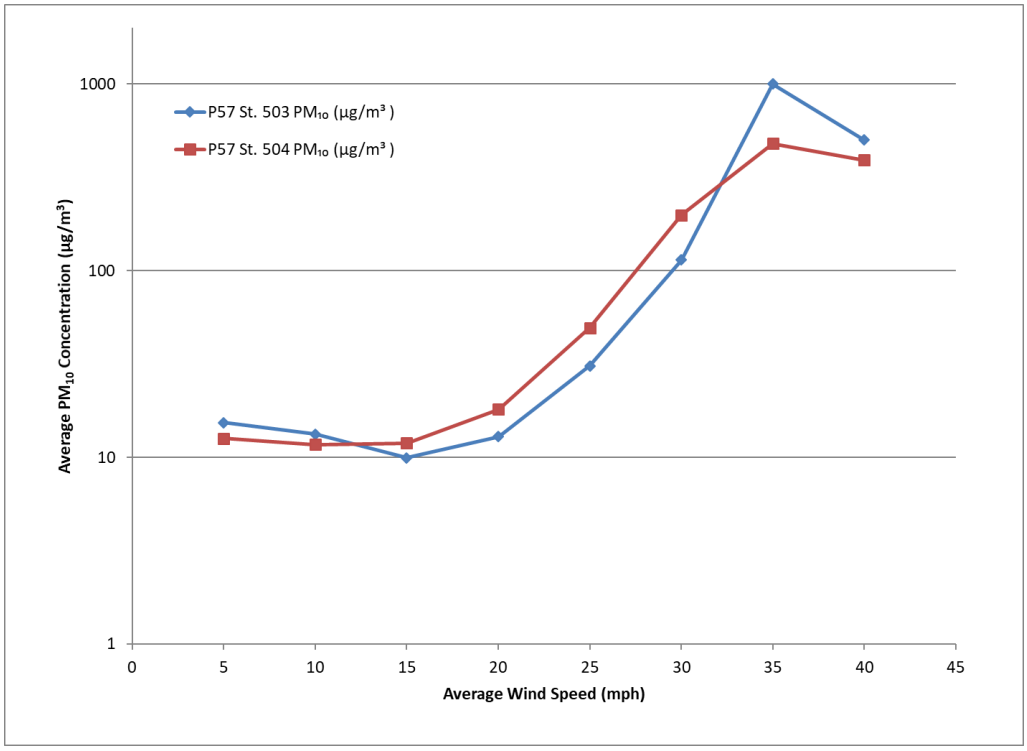

Figure C-29. The relationship between PM_{10} and average wind speed for the Project 57 stations for 2015 to 2019.

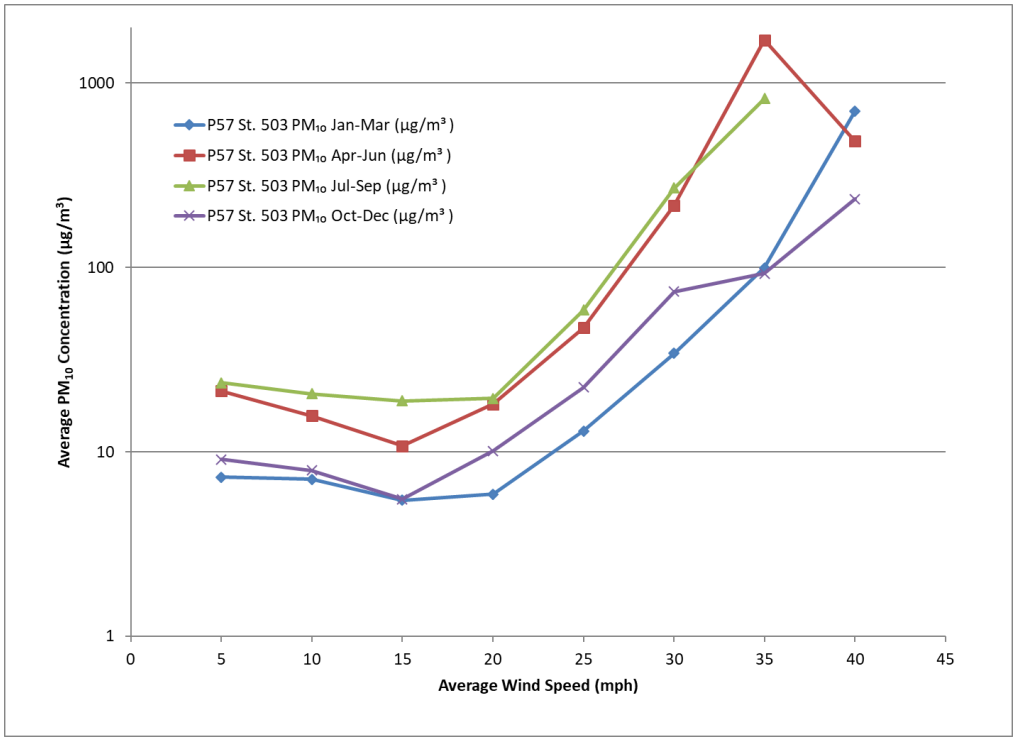

Figure C-30. The relationship between PM_{10} and average wind speed, presented by quarter of the year, for Station 503 for 2015 to 2019.

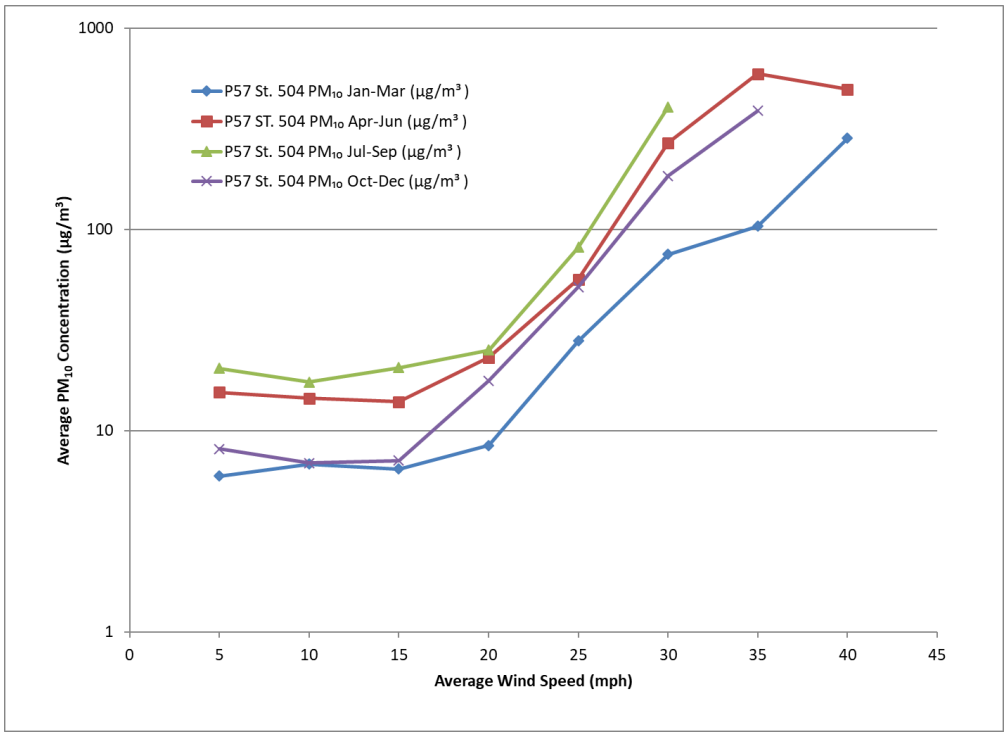

Figure C-31. The relationship between PM_{10} and average wind speed, presented by quarter of the year, for Station 504 for 2015 to 2019.

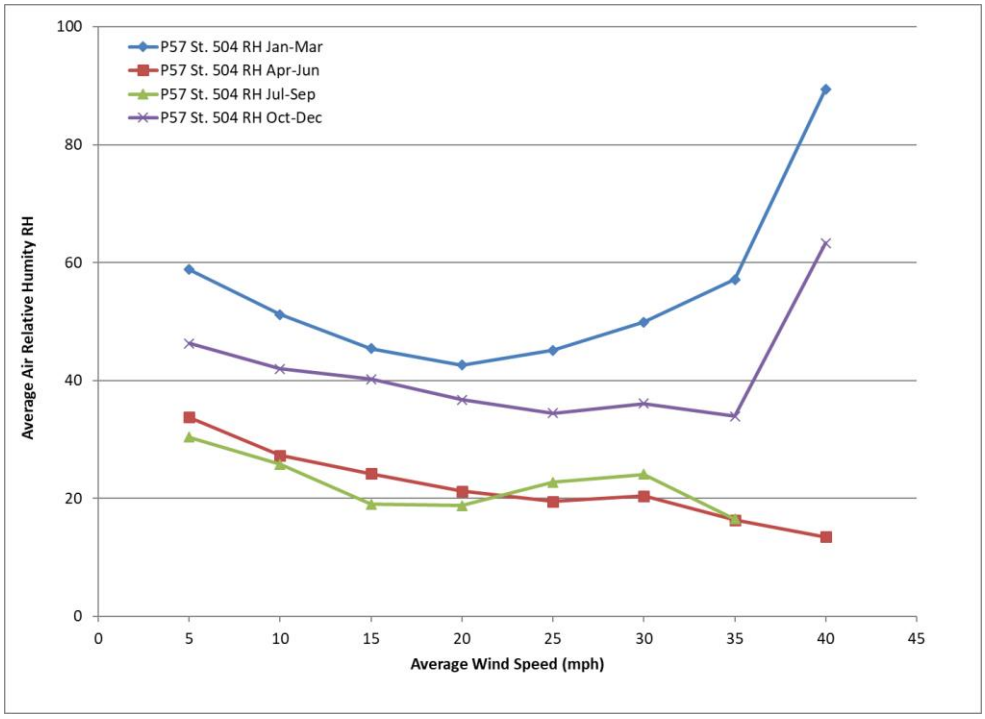

Figure C-32. The relationship between relative humidity and average wind speed, presented by quarter of the year, for Station 504 for 2015 to 2019.

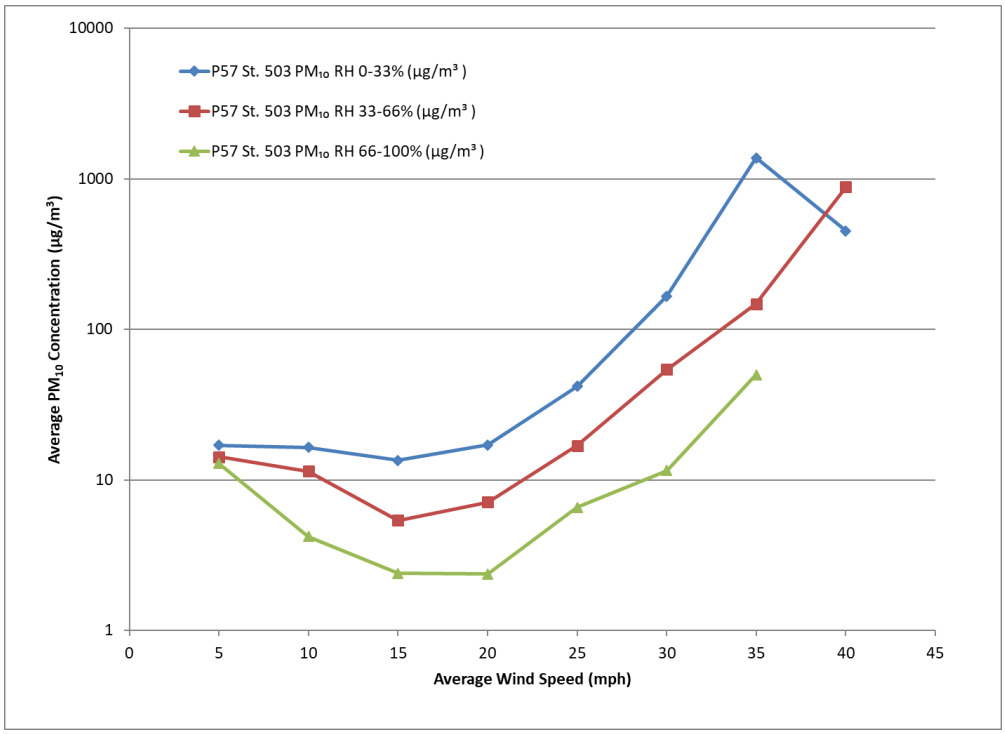

Figure C-33. The relationship between PM_{10} and average wind speed, presented by relative humidity, for Station 503 for 2015 to 2019.

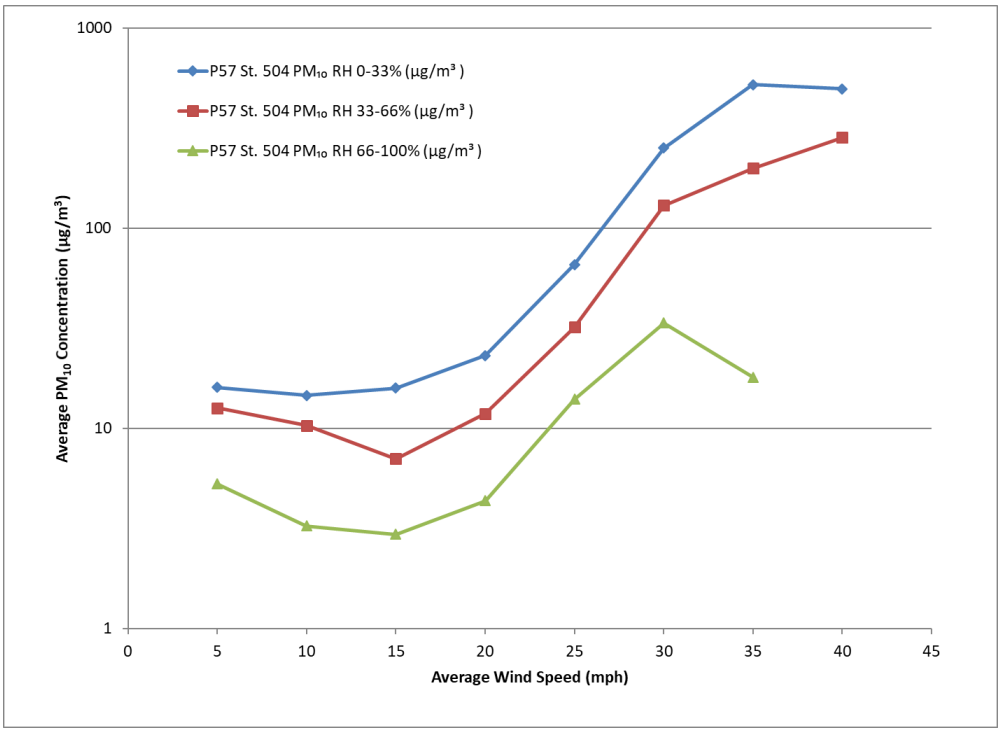

Figure C-34. The relationship between PM_{10} and average wind speed, presented by relative humidity, for Station 504 for 2015 to 2019.

Radionuclide Transport

The air filter samples represent a time series record of dust continuously collected during two-week periods at the monitoring stations. For many of the sampling periods, the gross alpha concentration is relatively low (generally less than 5×10^{-15} µCi/ml) and similar on the filters of the two stations (Figure C-35). This can be considered a local background value. When deviations from this local background occur, one station generally has significantly higher gross alpha concentration compared with the other during the same sampling period.

Relative to the local background, higher gross alpha measurements at Station 503 (indicated by blue arrows on Figure C-35) that are not matched by similar concentrations at Station 504 indicate dust transport from the contamination area due to high winds from the south suspending contaminants as they travel across the site. Similarly, higher gross alpha measurements at Station 504 (indicated by orange arrows on Figure C-35) that are unmatched at Station 503 indicate transport of contaminants due to winds coming from the north. More frequent, and higher concentration, gross alpha measurements at Station 504 compared with Station 503 (Figure C-36) indicate that contaminant transport occurs more often during winds from the north, moving dust from the Project 57 contamination area to be intercepted by the air sampler at Station 504 south of the area. These events are predominantly between December and June. The observations are consistent with the greater frequency of winds from the north observed at the stations and they suggest that the net migration of windblown material from Project 57 is toward the south and southeast.

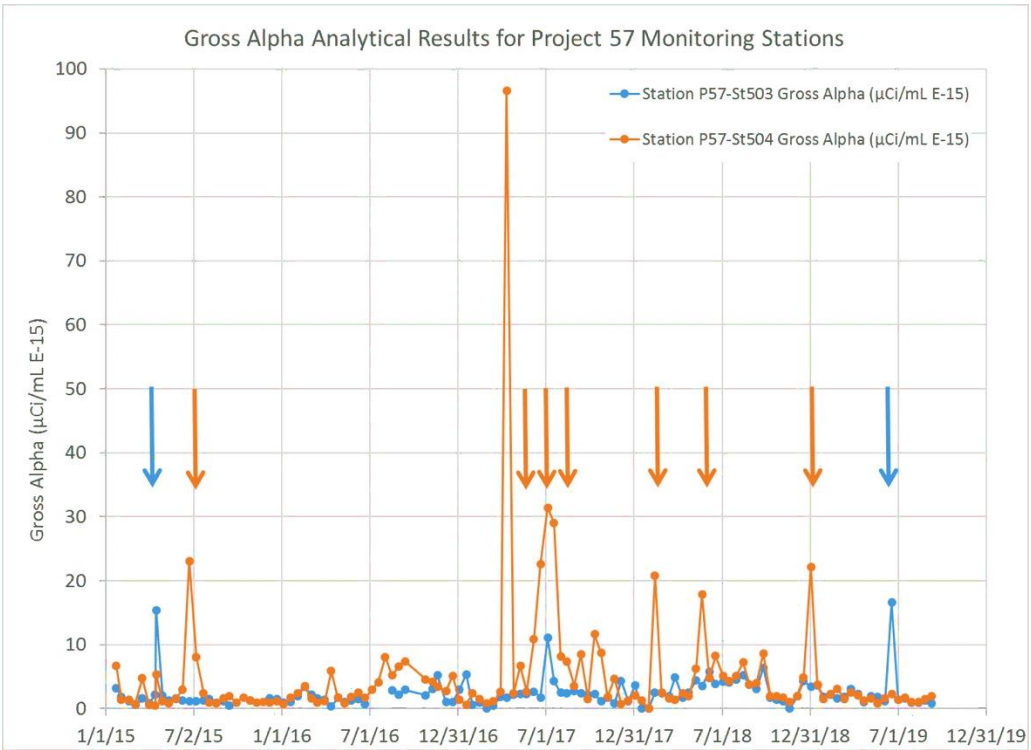

Figure C-35. Time series gross alpha concentrations for the Project 57 stations.

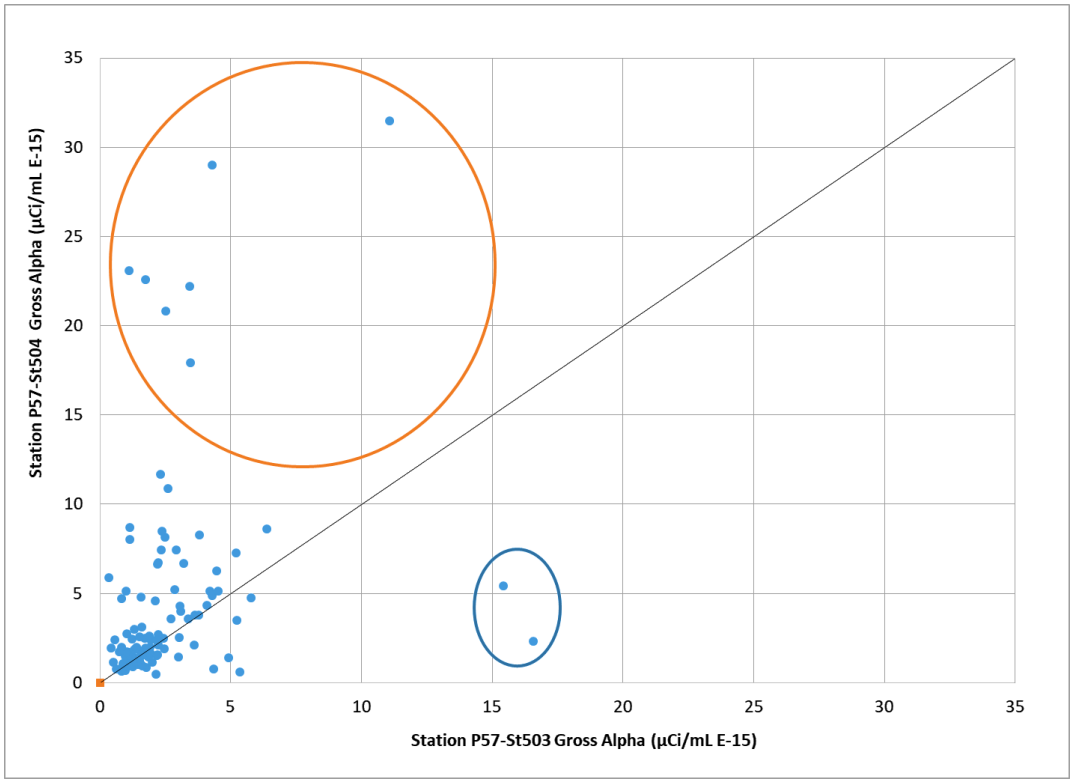

Figure C-36. The correlation between gross alpha concentrations measured at Stations 503 and 504 for 2015 to 2019. The circles enclose the gross alpha analyses highlighted by the arrows in Figure C-35.

Clean Slate Sites

The data summarized for the Clean Slate sites were collected between May 2017 and December 2019. Although monitoring at Clean Slate III and the nearby Range Operation Center for the TTR began in 2008 and monitoring at Clean Slate I began in 2011, the two stations at Clean Slate II and a second station at Clean Slate III were not installed until May 2017. Stations 401 and 403 are located north and southeast of the Clean Slate III contamination area, respectively, and Stations 404 and 405 are located north and southeast of the Clean Slate II contamination area, respectively (Figure C-37). Station 400 is located approximately five miles northwest of Clean Slate III. Station 402, formerly located at Clean Slate I is not included in this summary, but its information can be found in the annual monitoring reports from 2011 through 2017 (Appendix A).

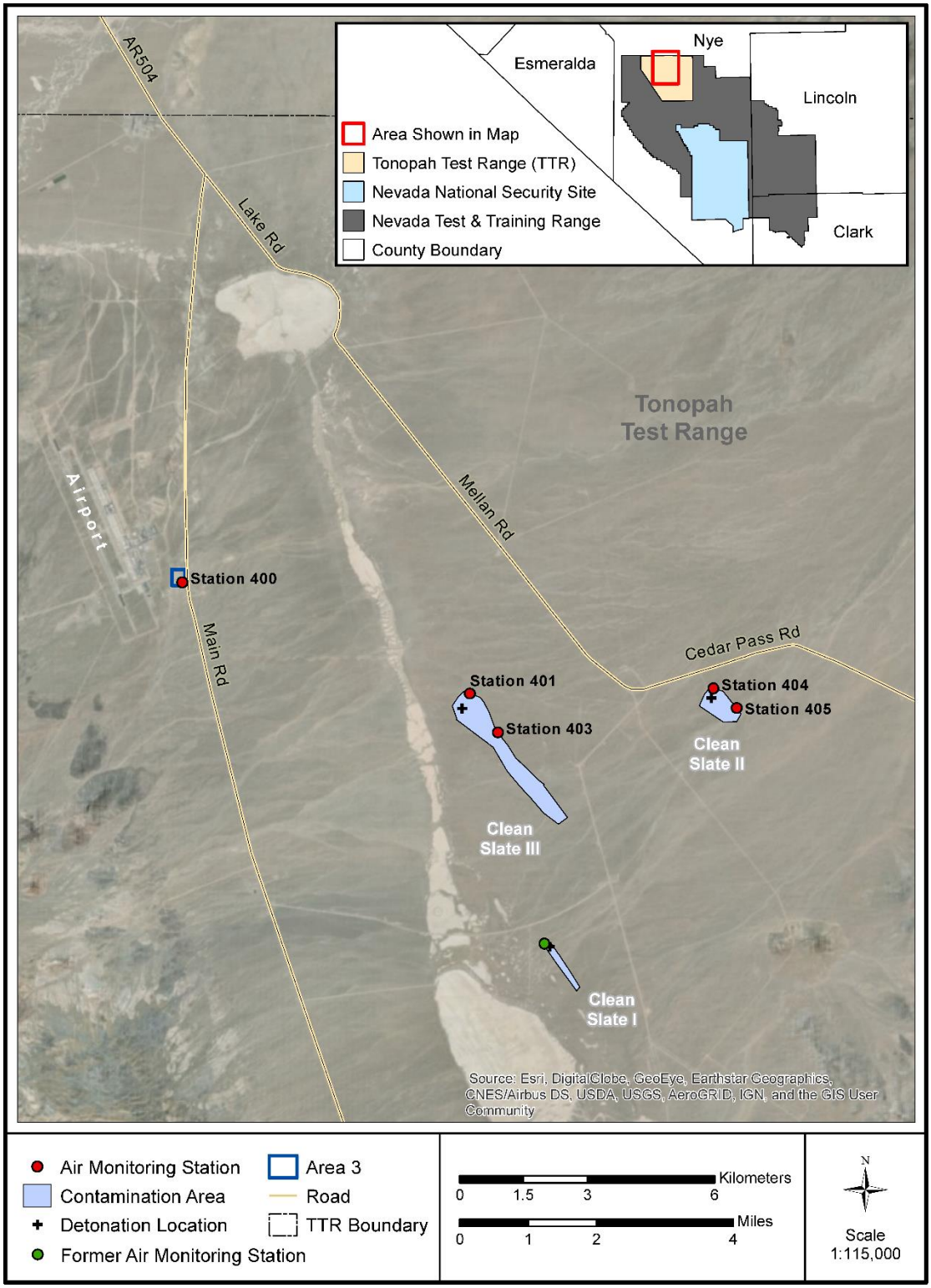

Figure C-37. The environmental monitoring stations relative to the Clean Slate sites.

Wind Speed and Direction

Wind roses for Clean Slate monitoring Stations 400, 401, 403, 404, and 405 (Figures C-38, C-39, C-40, C-41, and C-42, respectively) demonstrate the predominance of winds from the south and northwest during the year, particularly for sustained winds greater than 15 mph. The wind speed and direction is similar between all the Clean Slate stations, with the exception that the frequency of light winds below 15 mph from the east is significantly higher at Clean Slate II Stations 404 and 405 than elsewhere. Of the winds greater than 15 mph, they are most frequently from the north during the last quarter of the year (October through December) and from the south during the rest of the year (Figures C-43, C-44, C-45, C-46, and C-47).

High winds are most common during the spring (Figures C-48 and C-49). Winds greater than 25 mph occur approximately 0.2 percent of the year and winds greater than 15 mph occur approximately 12 percent to 15 percent of the year (Figure C-50). Winds in excess of 25 mph are more frequent at Station 401 compared with the other stations.

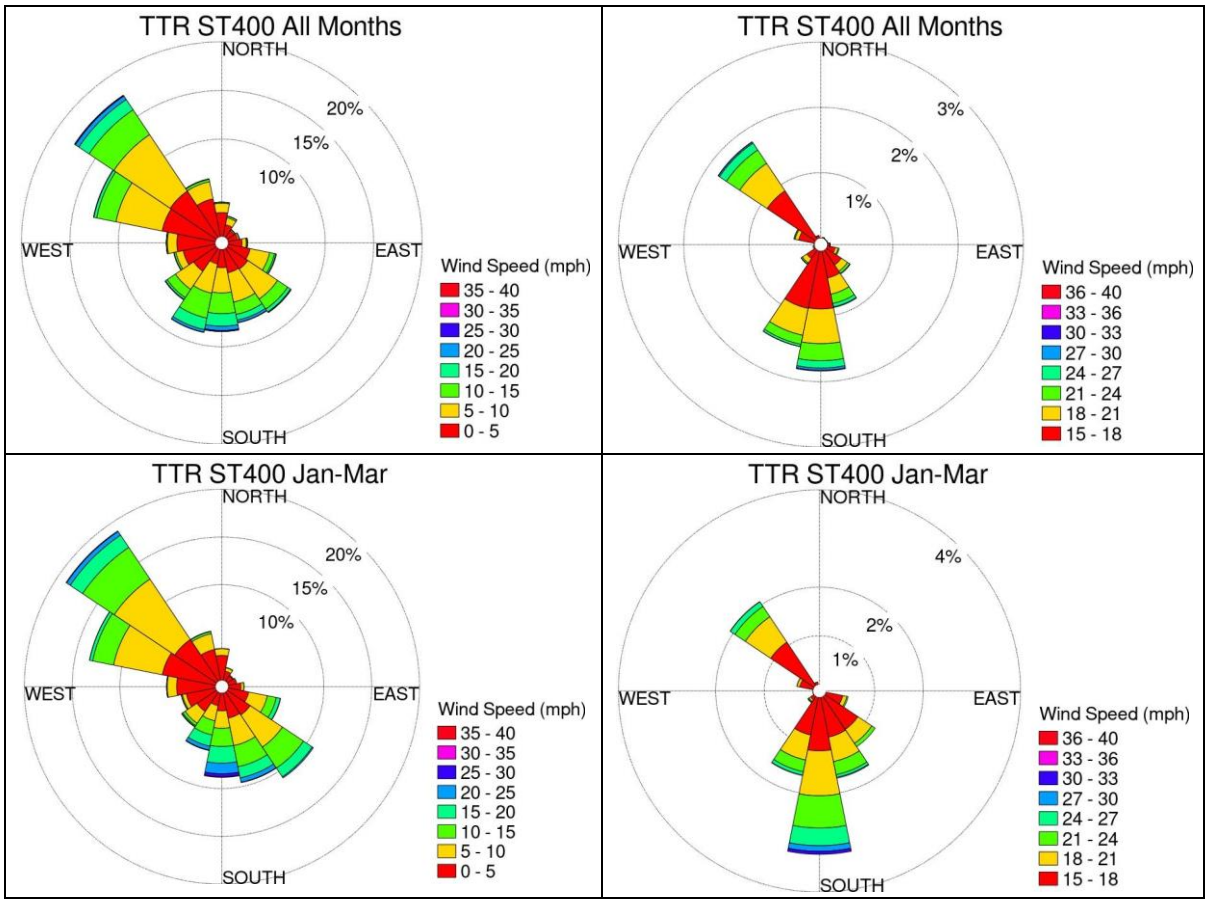

Figure C-38. TTR Station 400 wind rose figures for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph.

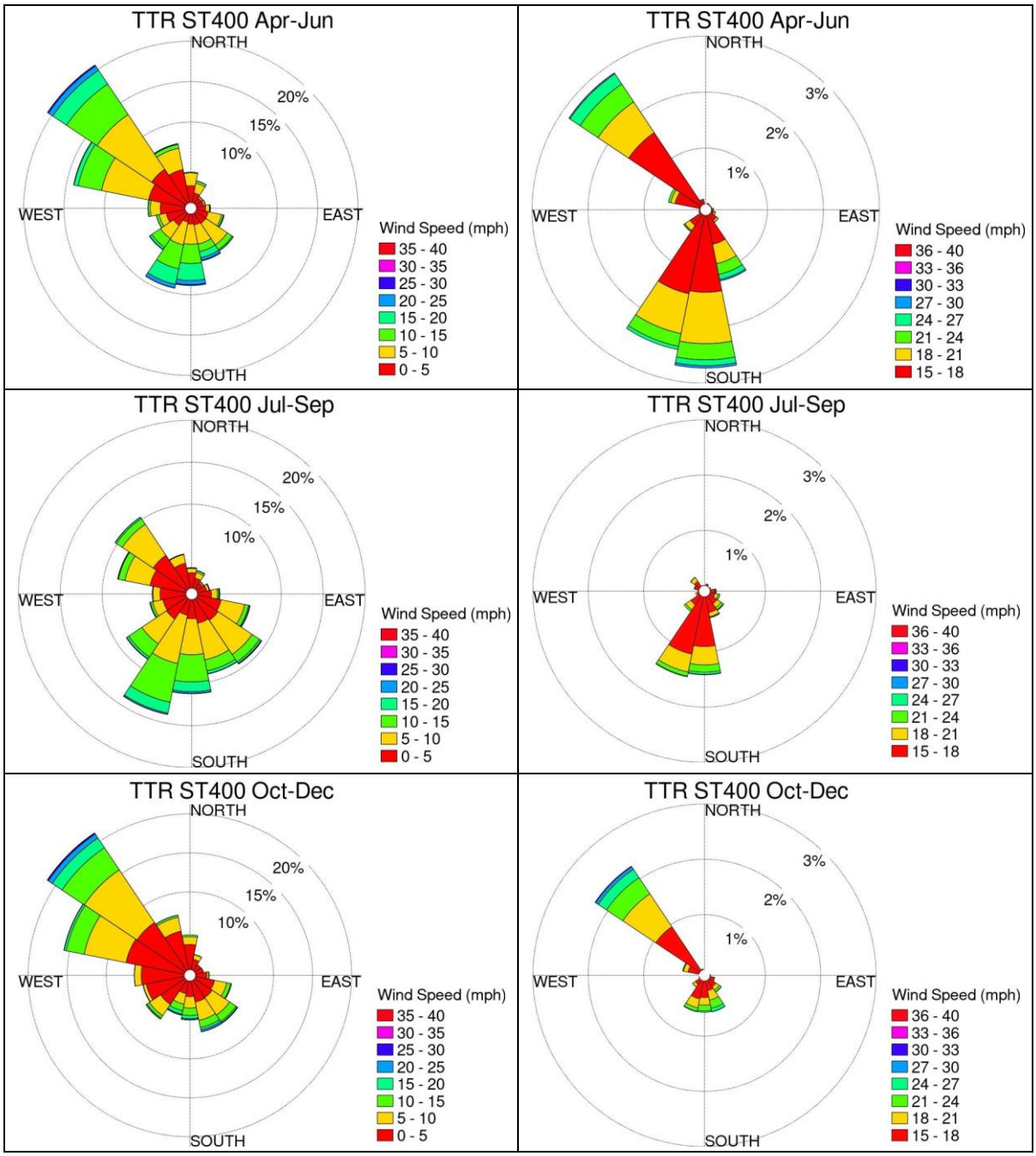

Figure C-38. TTR Station 400 wind rose figures for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph (continued).

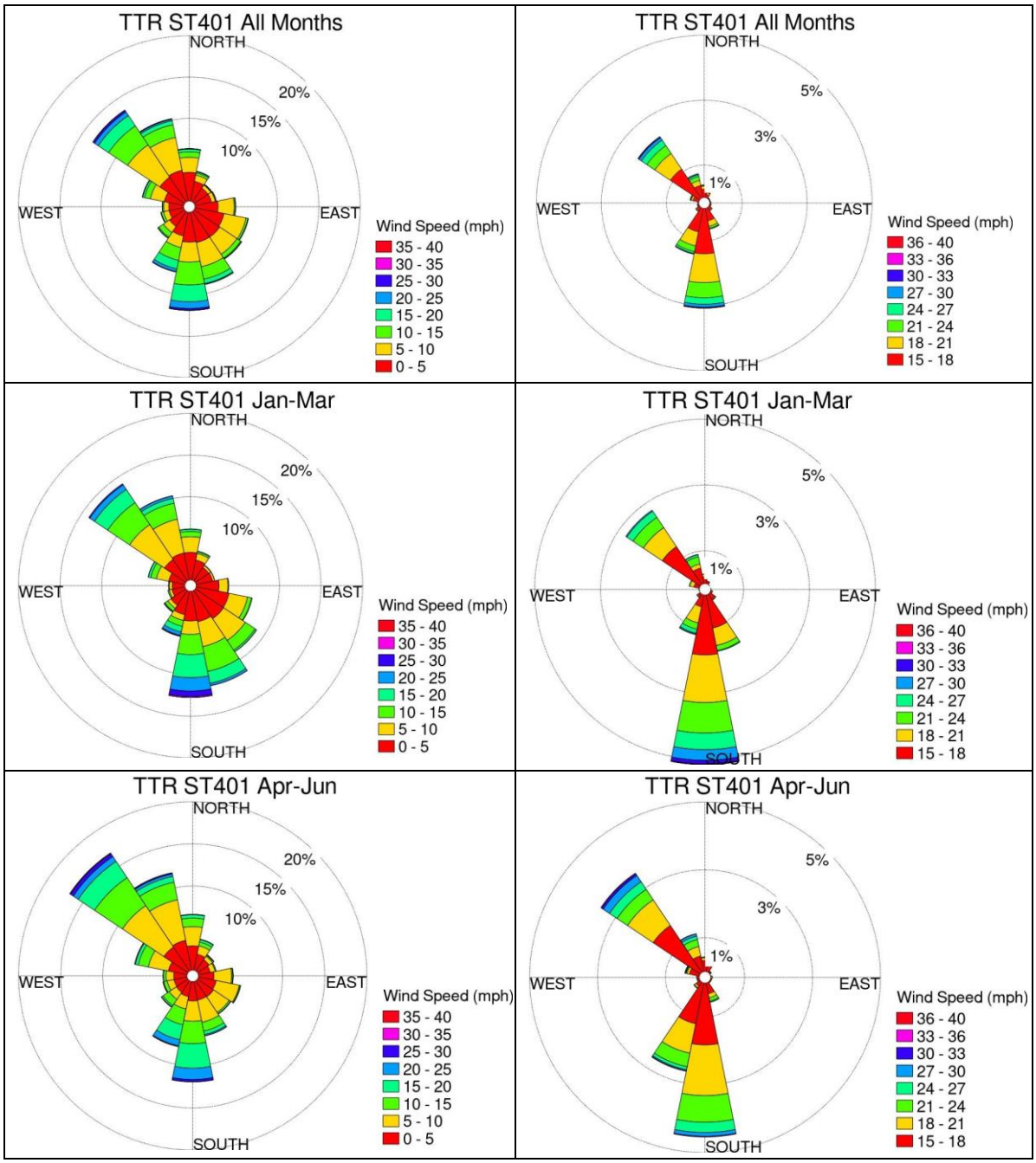

Figure C-39. TTR Station 401 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph.

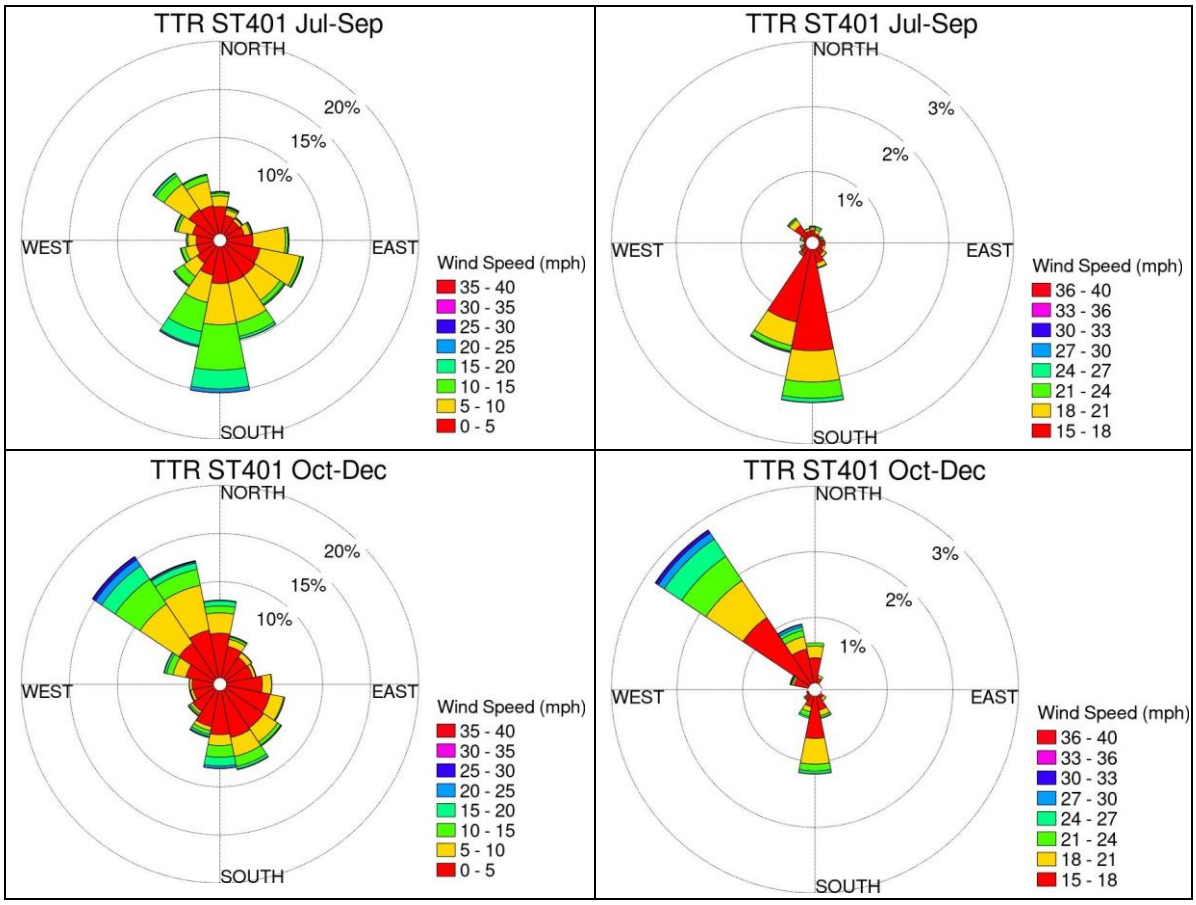

Figure C-39. TTR Station 401 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph (continued).

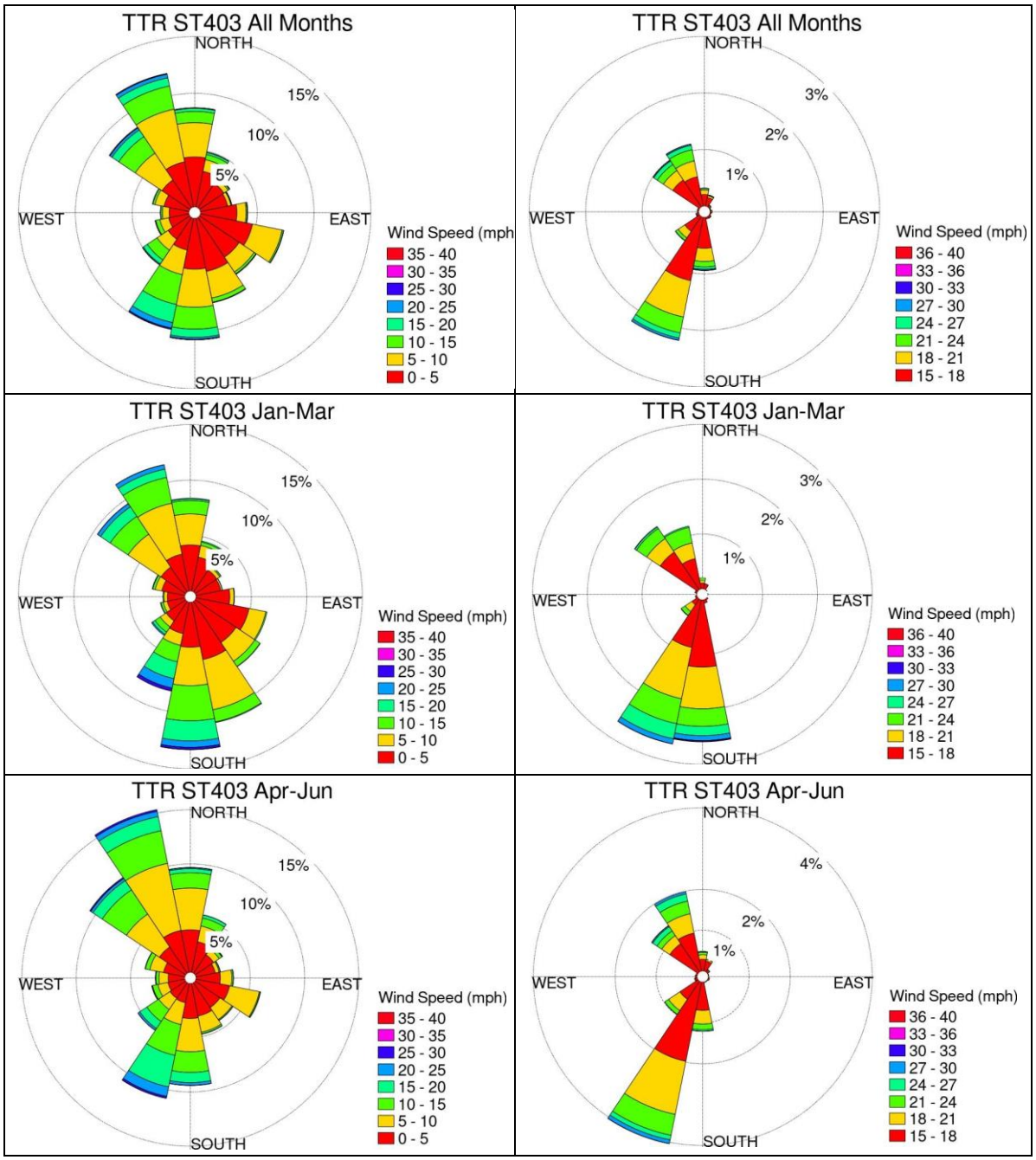

Figure C-40. TTR Station 403 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph.

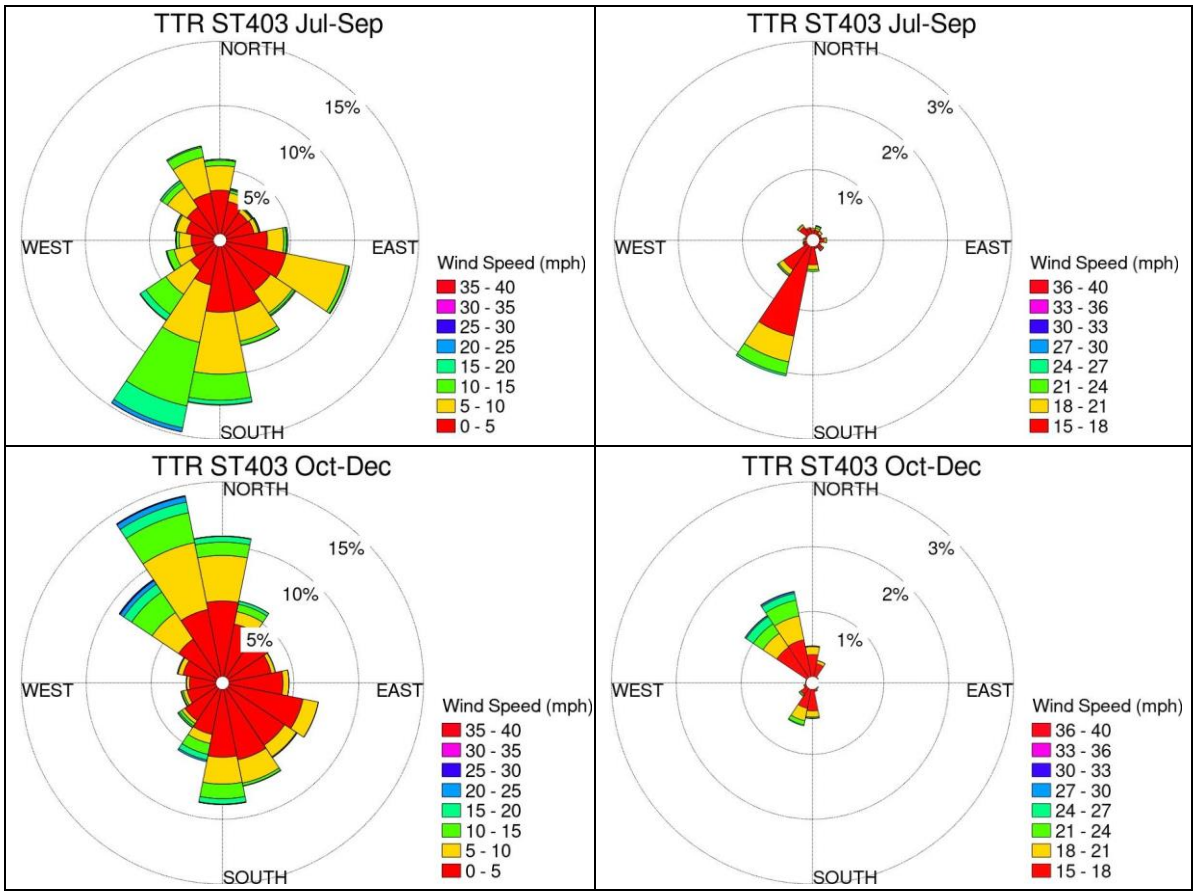

Figure C-40. TTR Station 403 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph (continued).

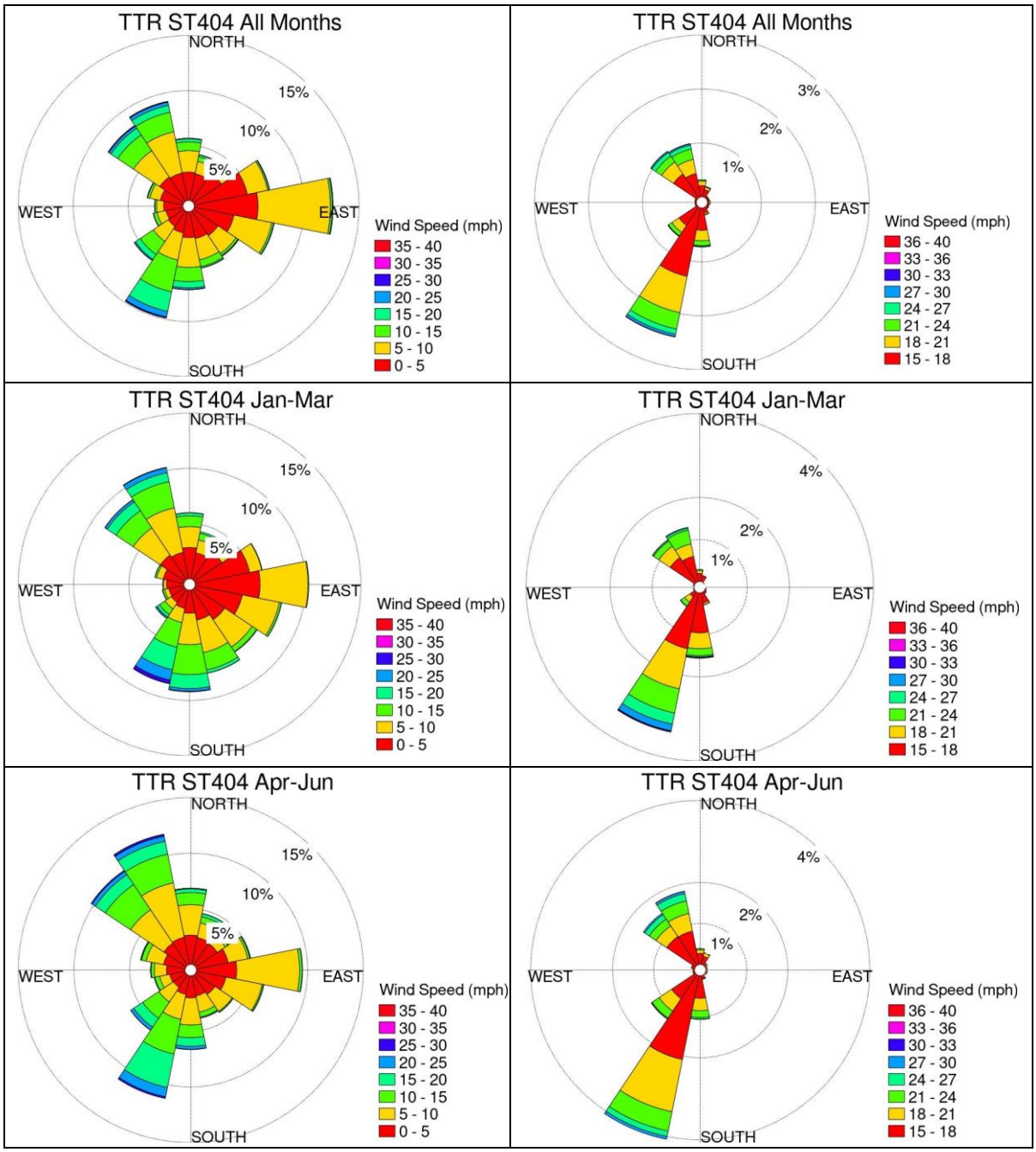

Figure C-41. TTR Station 404 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph.

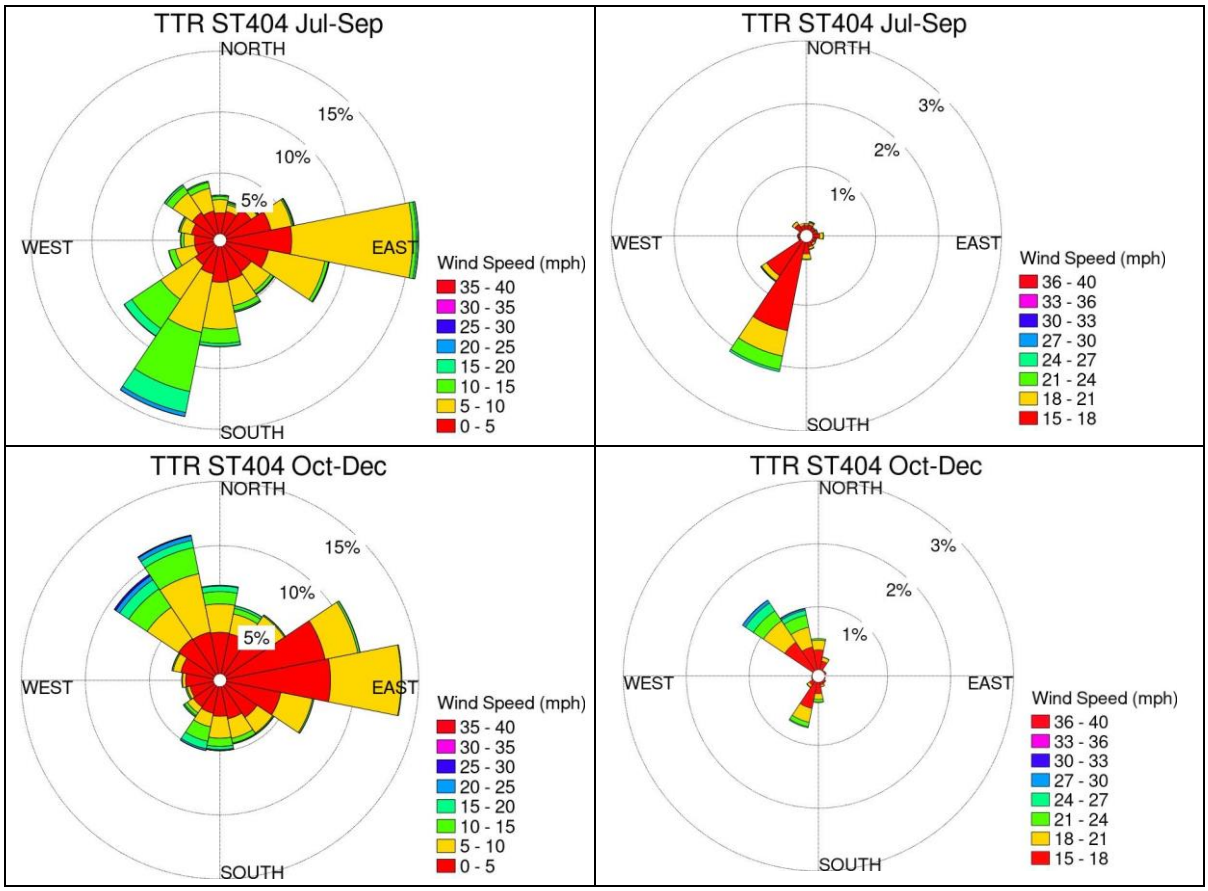

Figure C-41. TTR Station 404 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph (continued).

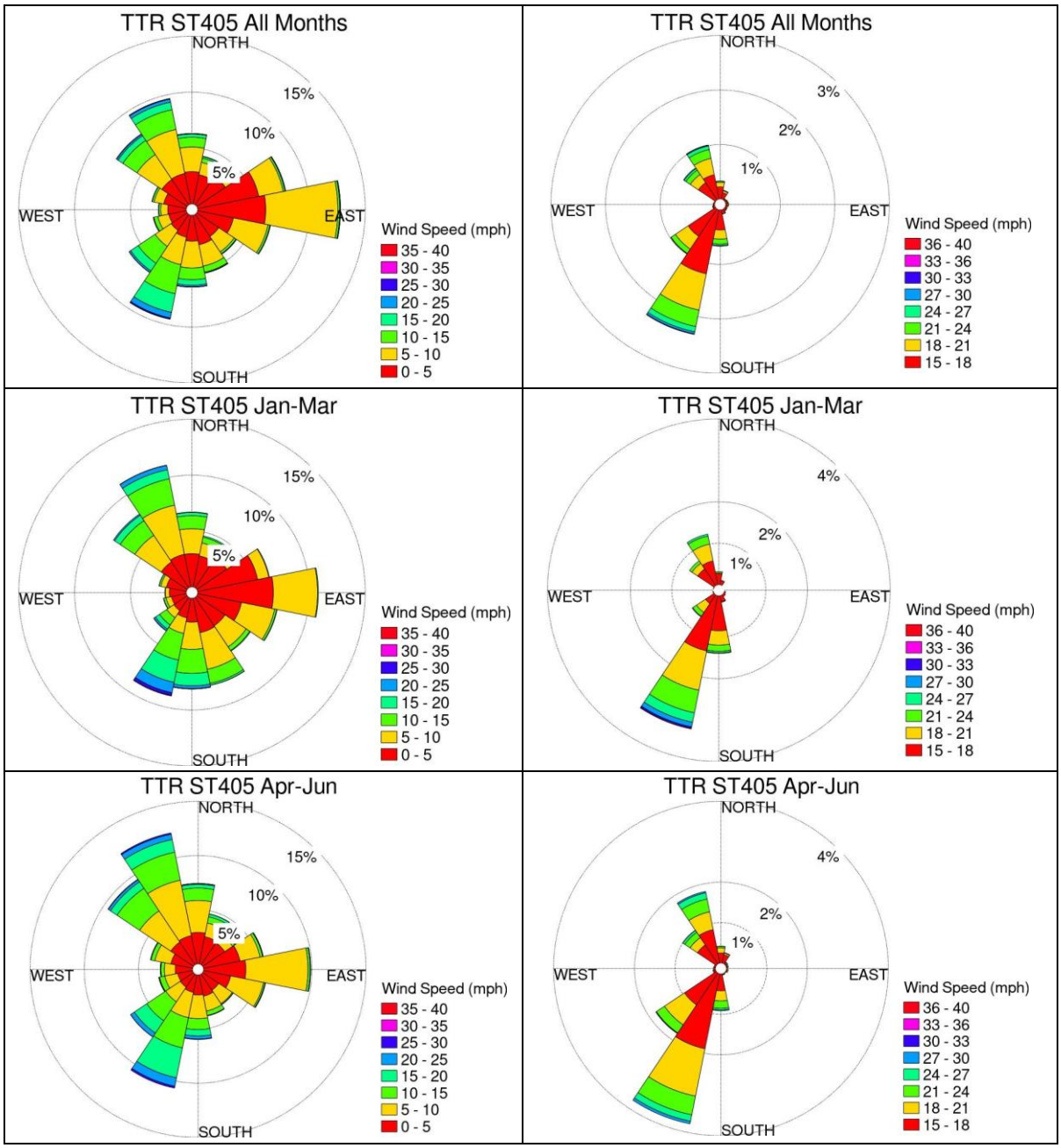

Figure C-42. TTR Station 405 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph.

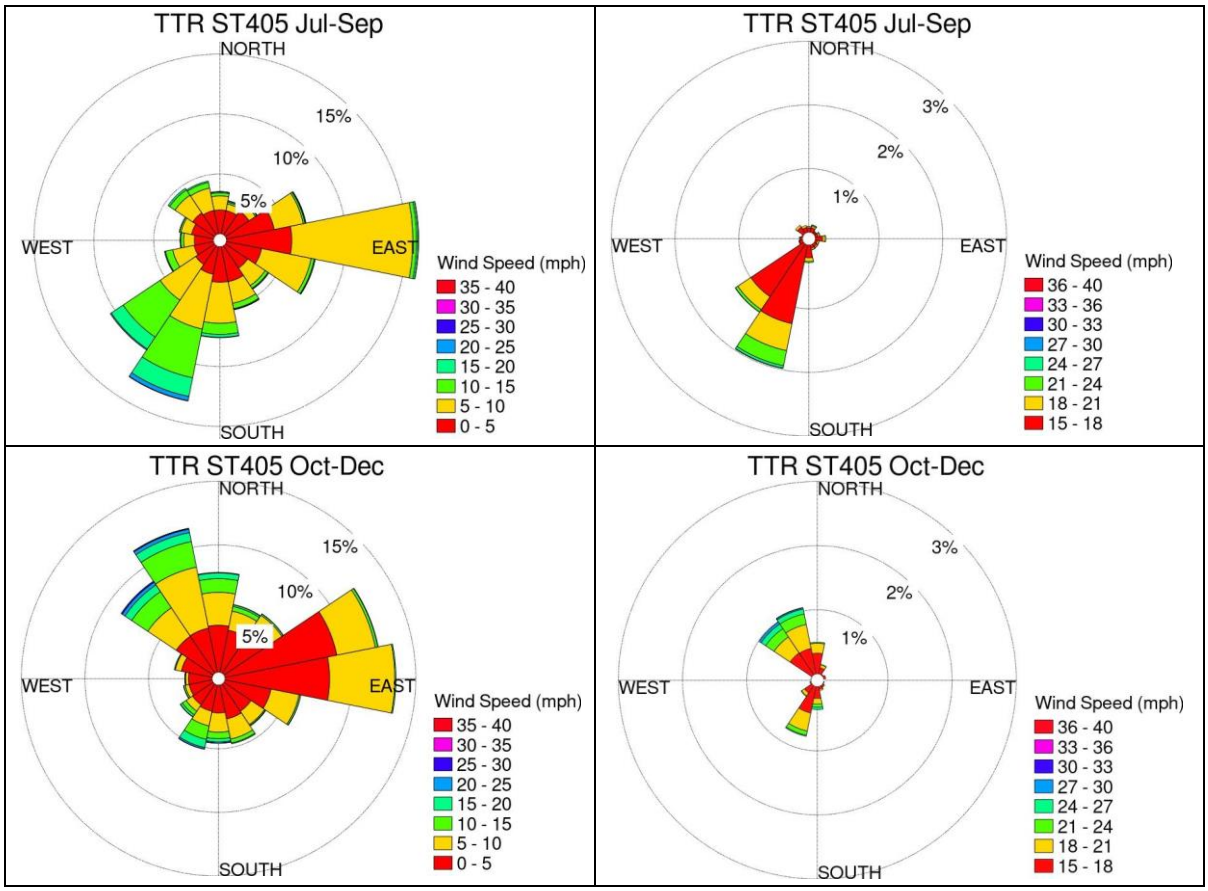

Figure C-42. TTR Station 405 wind roses for data collected from May 2017 to December 2019 for all months (top row) and quarterly. The left column shows data for all winds and the right column shows data for winds greater than 15 mph (continued).

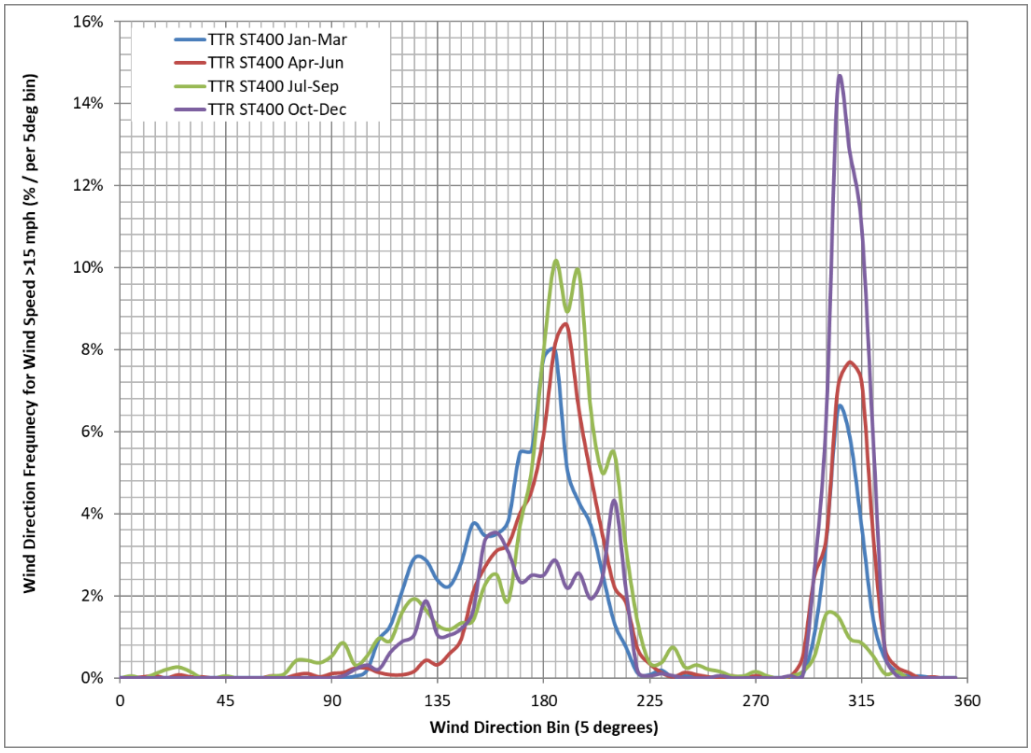

Figure C-43. Wind direction frequency for each three-month period at Station 400 for May 2017 to December 2019.

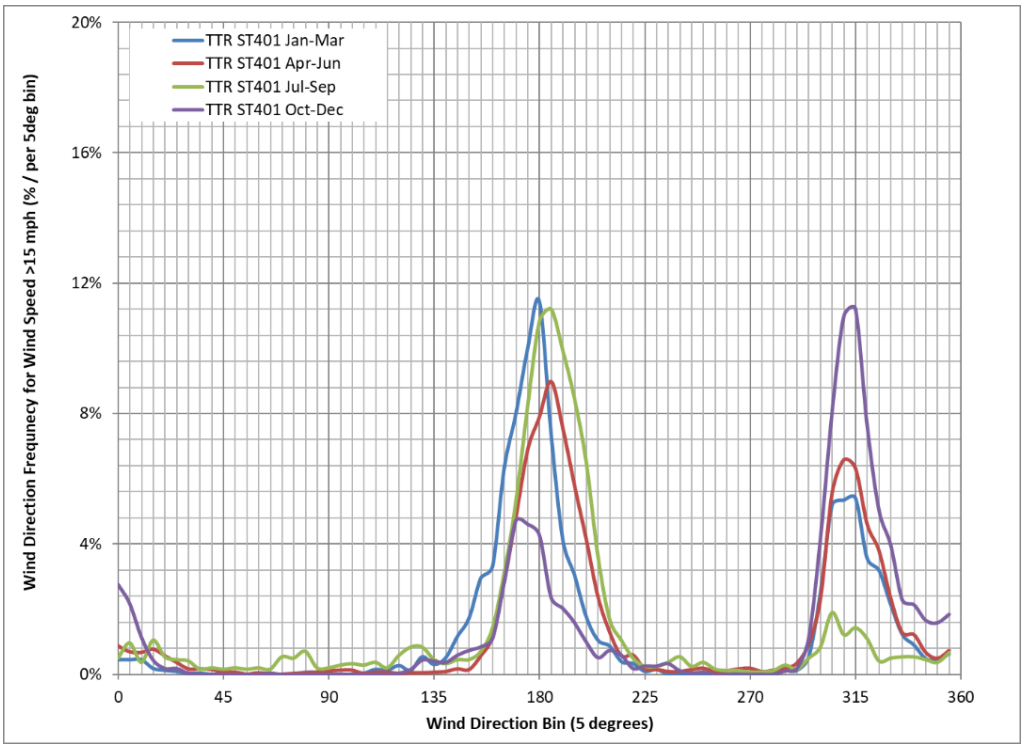

Figure C-44. Wind direction frequency for each three-month period at Station 401 for May 2017 to December 2019.

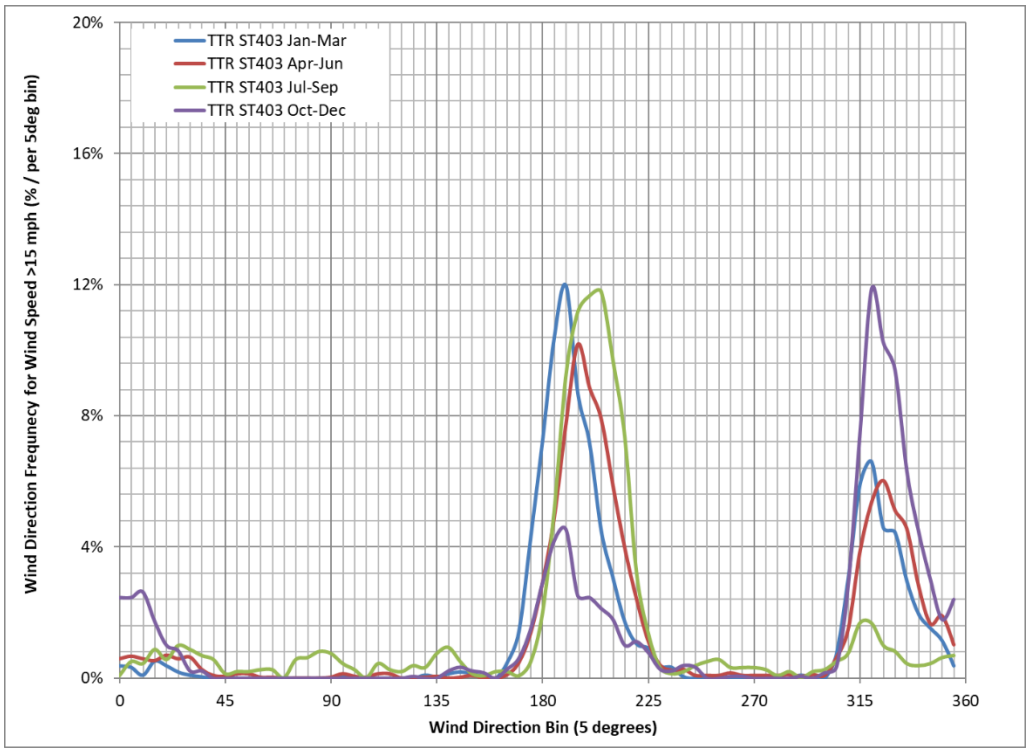

Figure C-45. Wind direction frequency for each three-month period at Station 403 for May 2017 to December 2019.

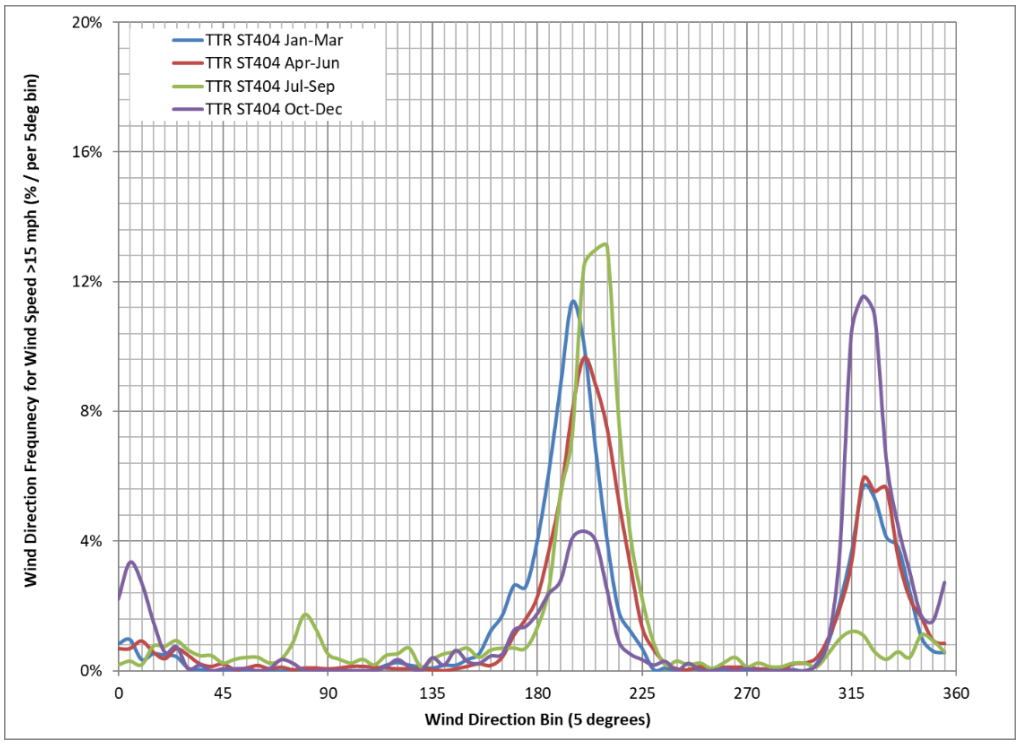

Figure C-46. Wind direction frequency for each three-month period at Station 404 for May 2017 to December 2019.

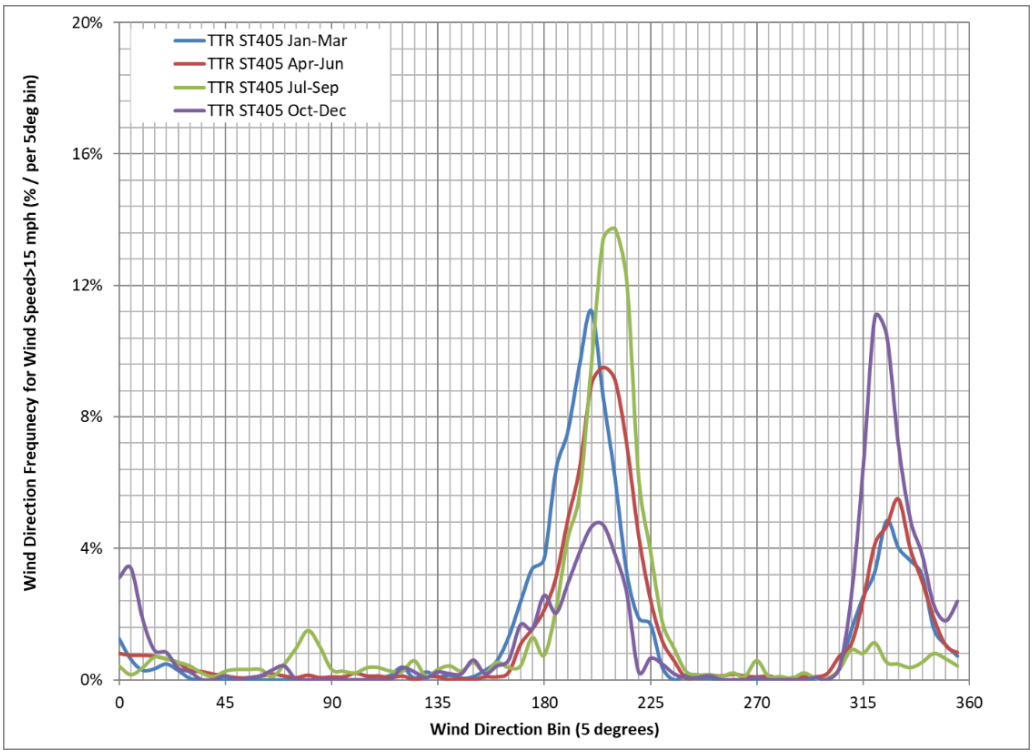

Figure C-47. Wind direction frequency for each three-month period at Station 405 for May 2017 to December 2019.

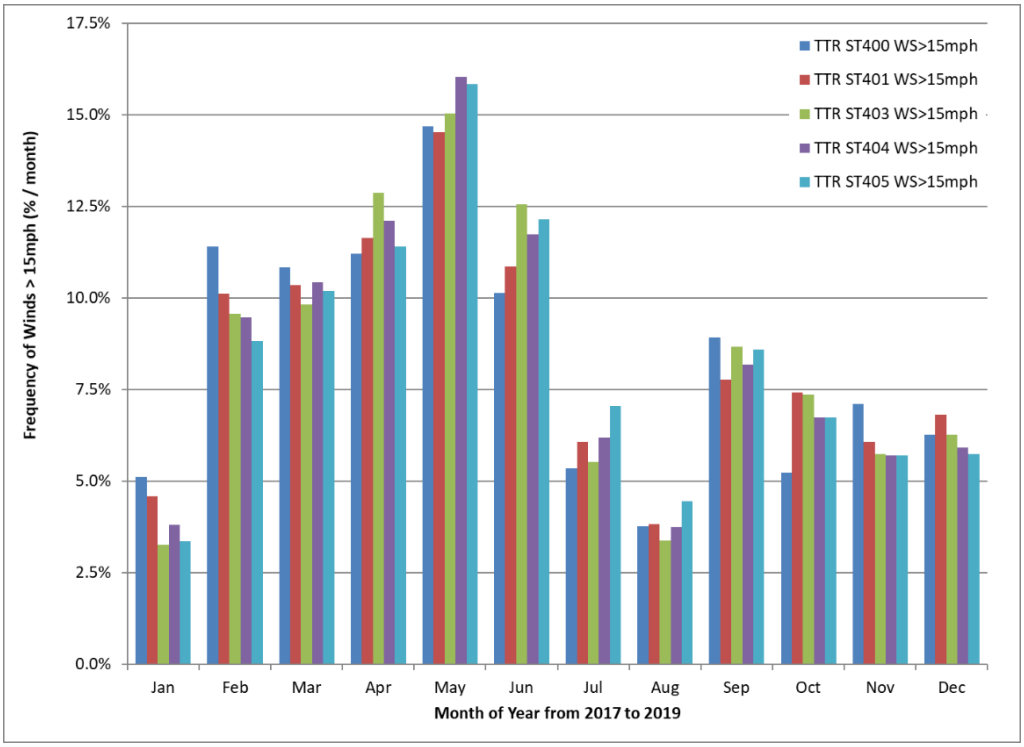

Figure C-48. Monthly wind frequency distribution of winds greater than 15 mph for May 2017 to December 2019.

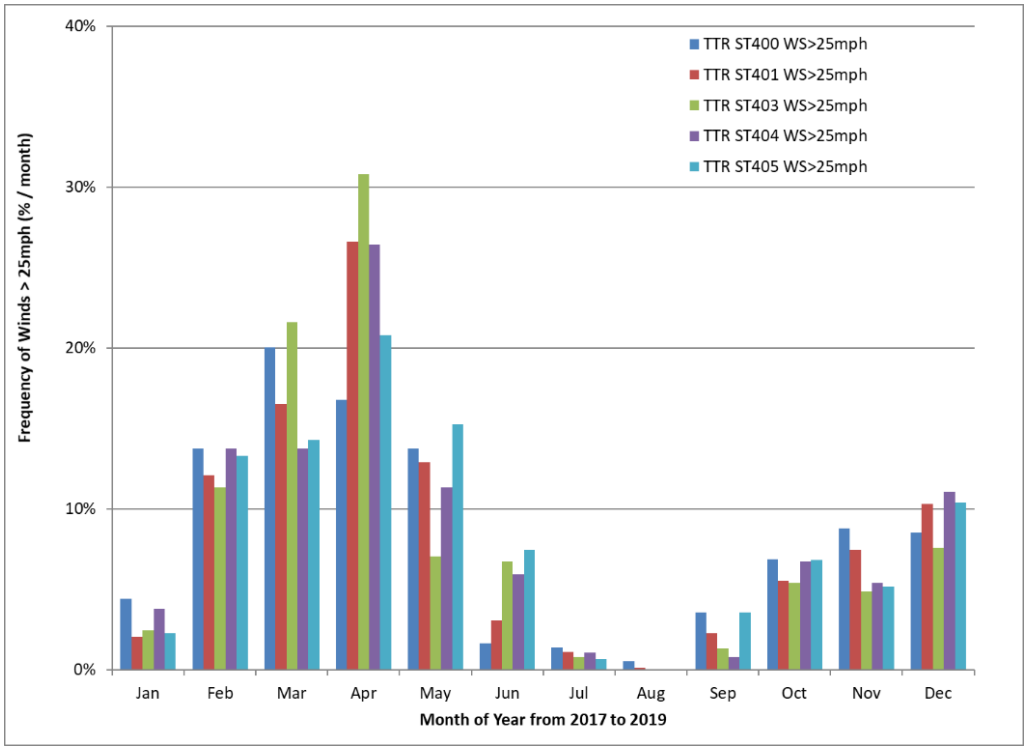

Figure C-49. Monthly wind frequency distribution of winds greater than 25 mph for May 2017 to December 2019.

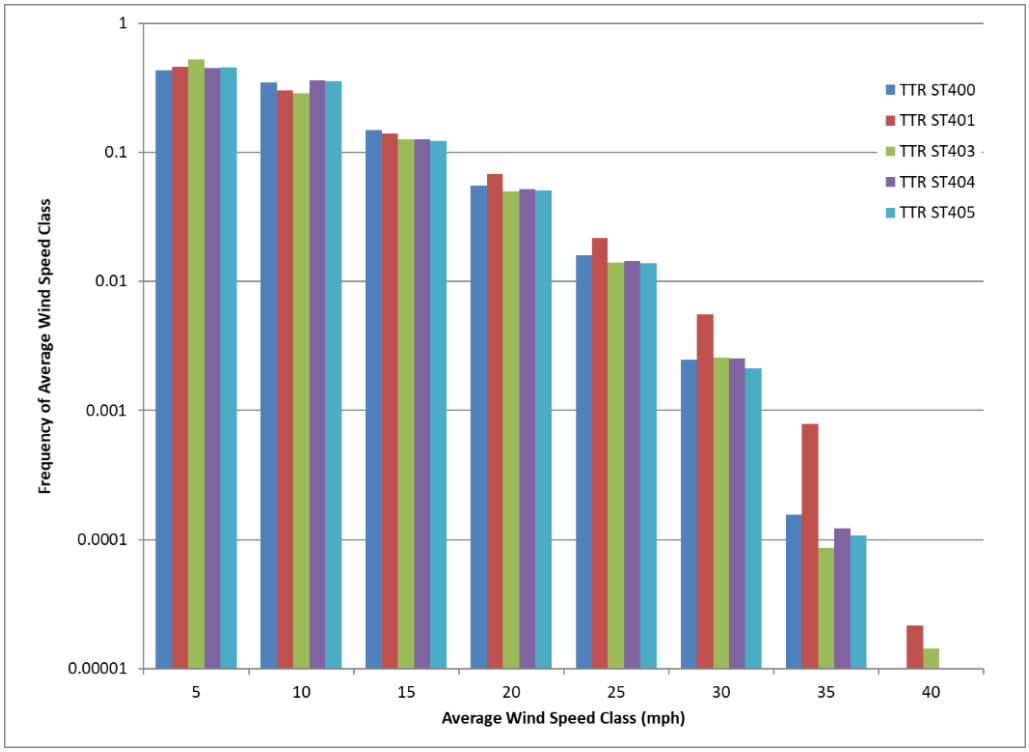

Figure C-50. Wind frequency distribution at the Clean Slate stations by 5 mph wind speed class for May 2017 to December 2019.

Dust Transport

The average PM_{10} concentration measured at the Clean Slate stations is nearly constant at approximately 10 µg/m^3 for winds below 15 mph (Figure C-51), which indicates that winds below 15 mph are not strong enough to suspend local dust. At wind speeds between 15 mph and 30 mph, the PM_{10} concentration increases exponentially. Station 400 tends to have lower dust concentrations during high winds, which is likely due to being surrounded by buildings and paved areas in contrast to the other monitoring stations. The dust concentrations at Stations 403 and 405—which are located southeast of Clean Slate III and II, respectively—level off at wind speeds in excess of 30 mph, suggesting a possibility of a more limited dust supply than at Stations 401 and 404, which are north of the contamination areas.

The first quarter of the year is generally characterized by the lowest PM_{10} concentrations at all wind speeds (Figures C-52 to C-56). Higher relative humidity (Figure C-57), lower air and soil temperature, higher precipitation, higher soil moisture content, and occasional frozen soil contribute to the lower dust generation during the winter months. Although the second quarter of the year has the highest frequency of winds above 15 mph and has low relative humidity and soil moisture content, it does not have the highest PM_{10} concentrations. It is suspected that vegetation growth (principally annuals and grasses) during the second quarter reduces wind shear at ground level, consequently reducing dust suspension. During the third and fourth quarters, much of the vegetation cover is likely gone. High relative humidity is consistently associated with lower PM_{10} concentrations throughout the range of wind speeds (Figures C-58 to C-62).

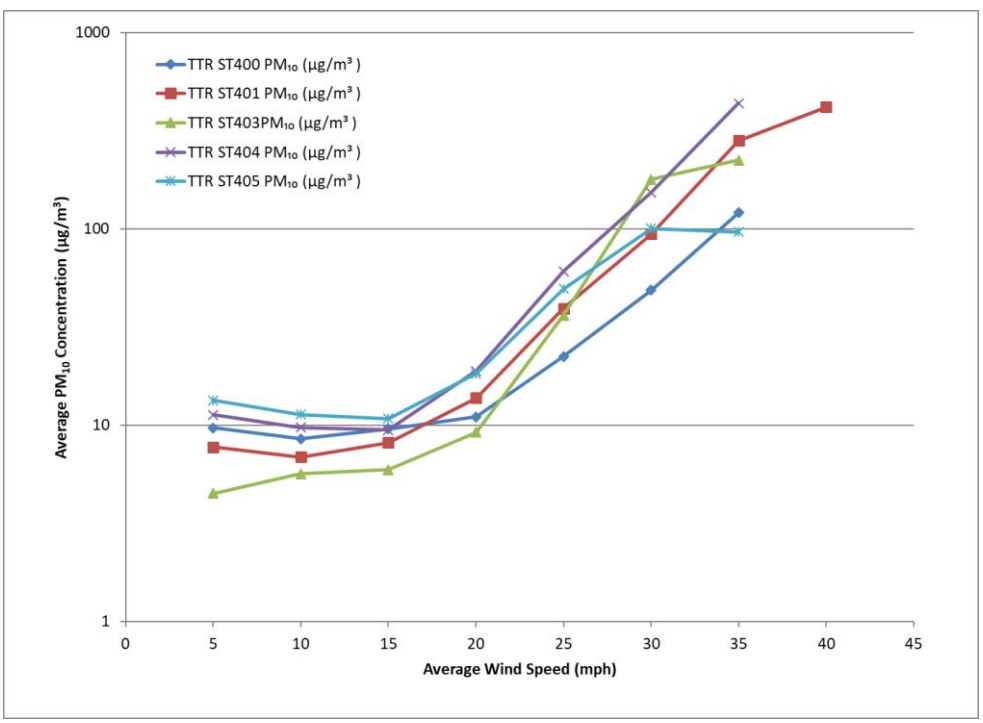

Figure C-51. Relationship between PM_{10} and average wind speed for the Clean Slate monitoring stations for May 2017 to December 2019.

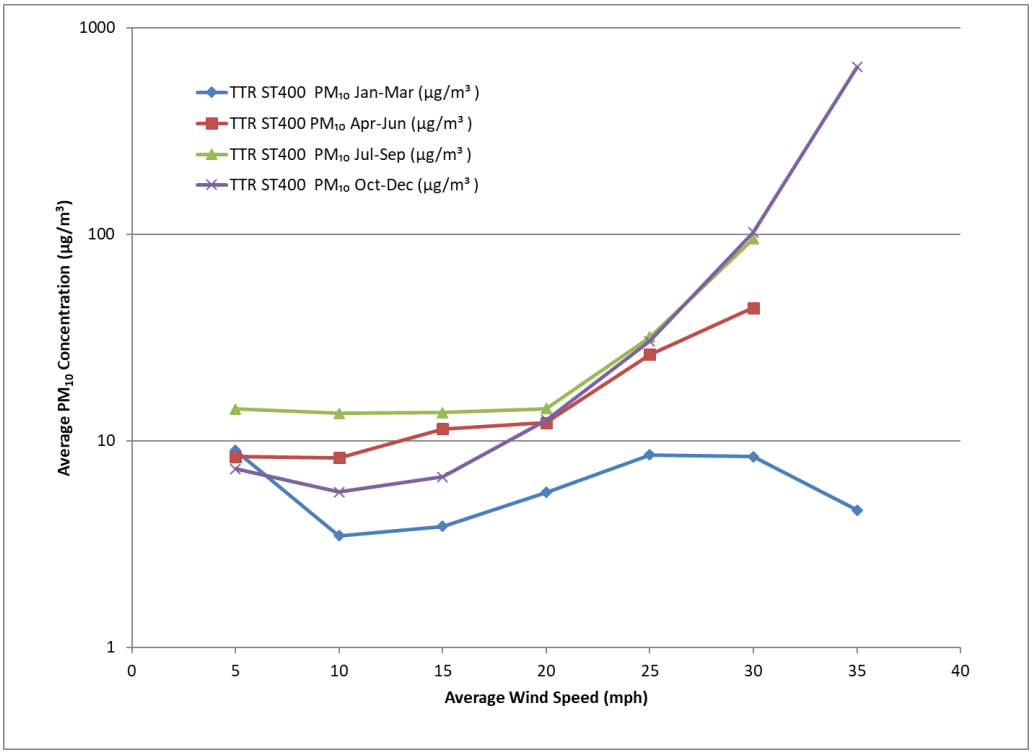

Figure C-52. Relationship between PM_{10} and average wind speed, presented by quarter, for Station 400 for May 2017 to December 2019.

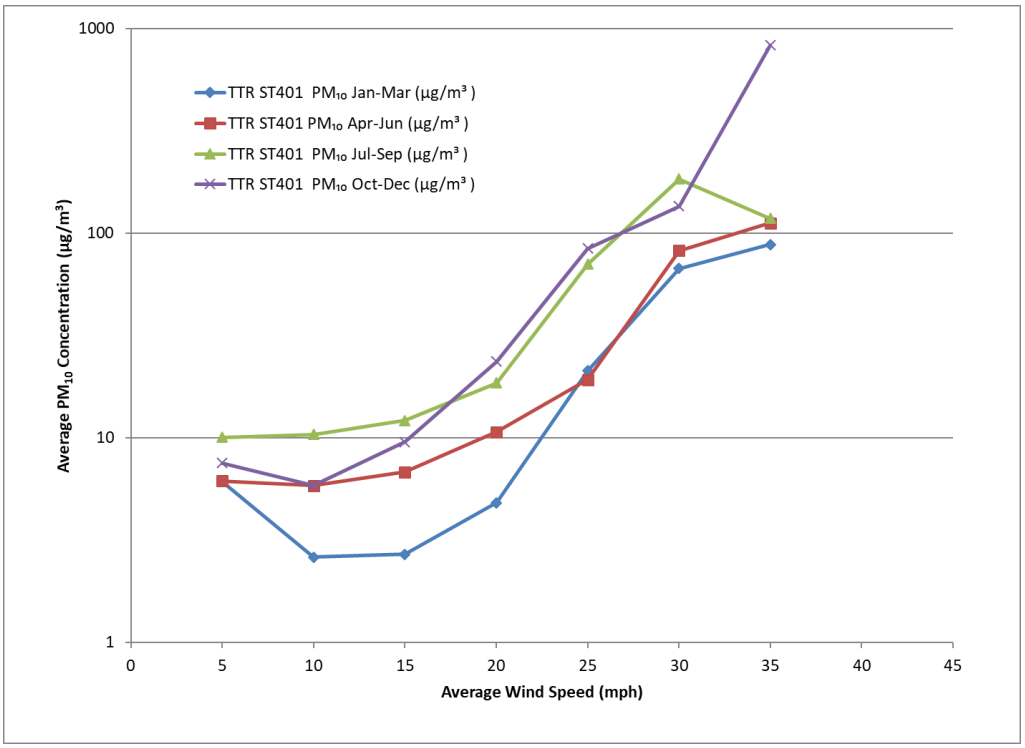

Figure C-53. Relationship between PM_{10} and average wind speed, presented by quarter, for Station 401 for May 2017 to December 2019.

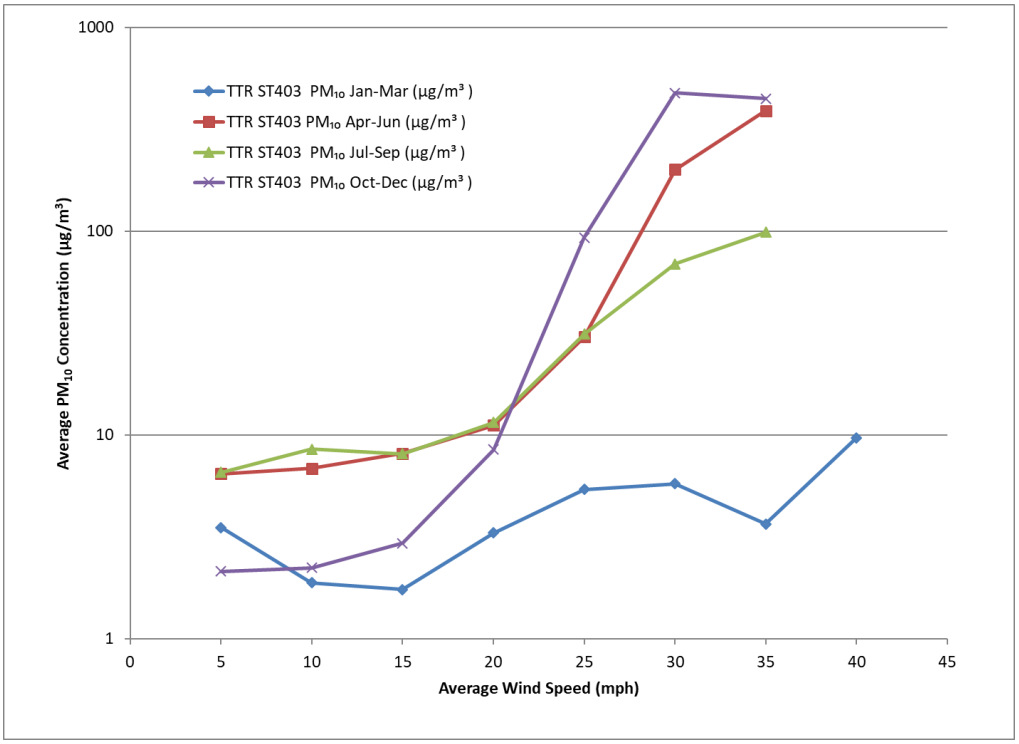

Figure C-54. Relationship between PM_{10} and average wind speed, presented by quarter, for Station 403 for May 2017 to December 2019.

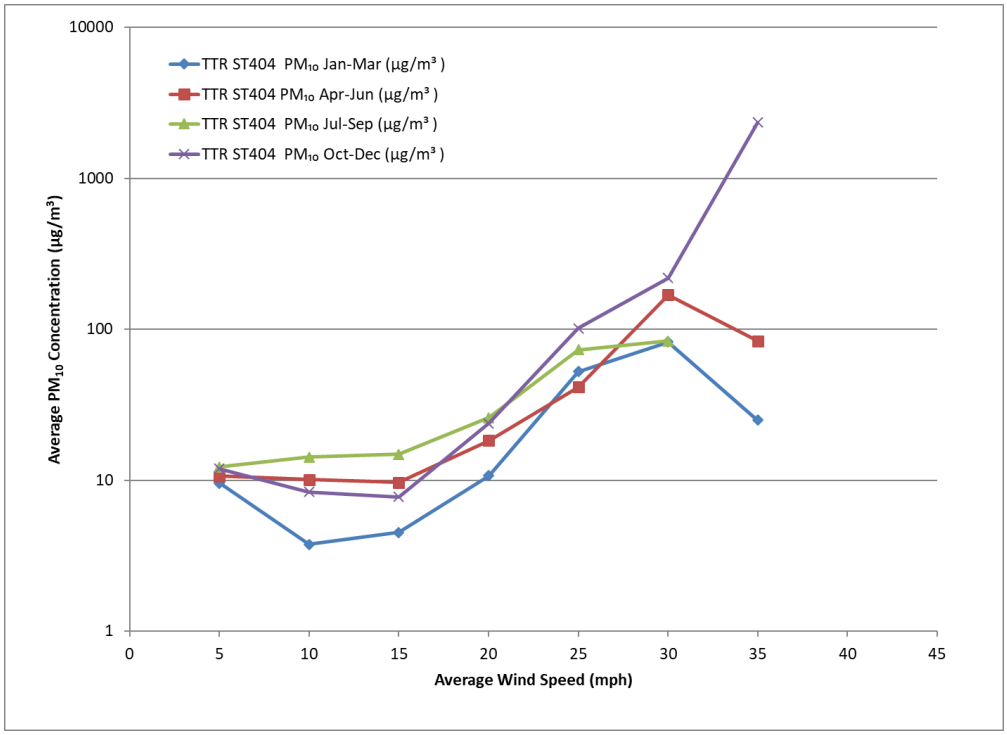

Figure C-55. Relationship between PM_{10} and average wind speed, presented by quarter, for Station 404 for May 2017 to December 2019.

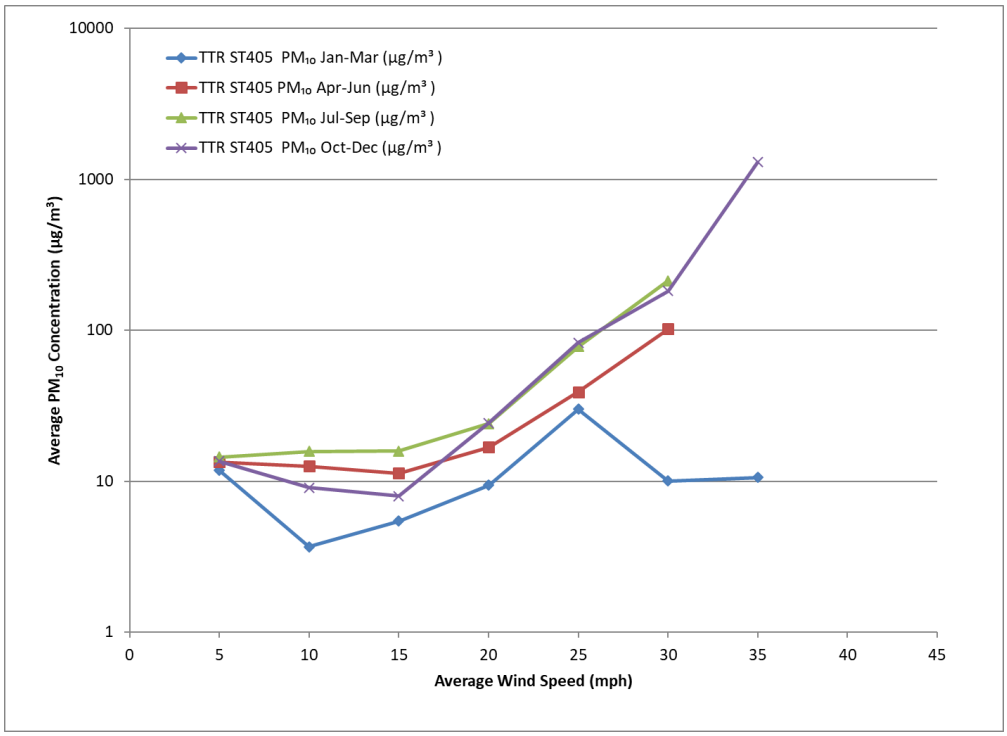

Figure C-56. Relationship between PM_{10} and average wind speed, presented by quarter, for Station 405 for May 2017 to December 2019.

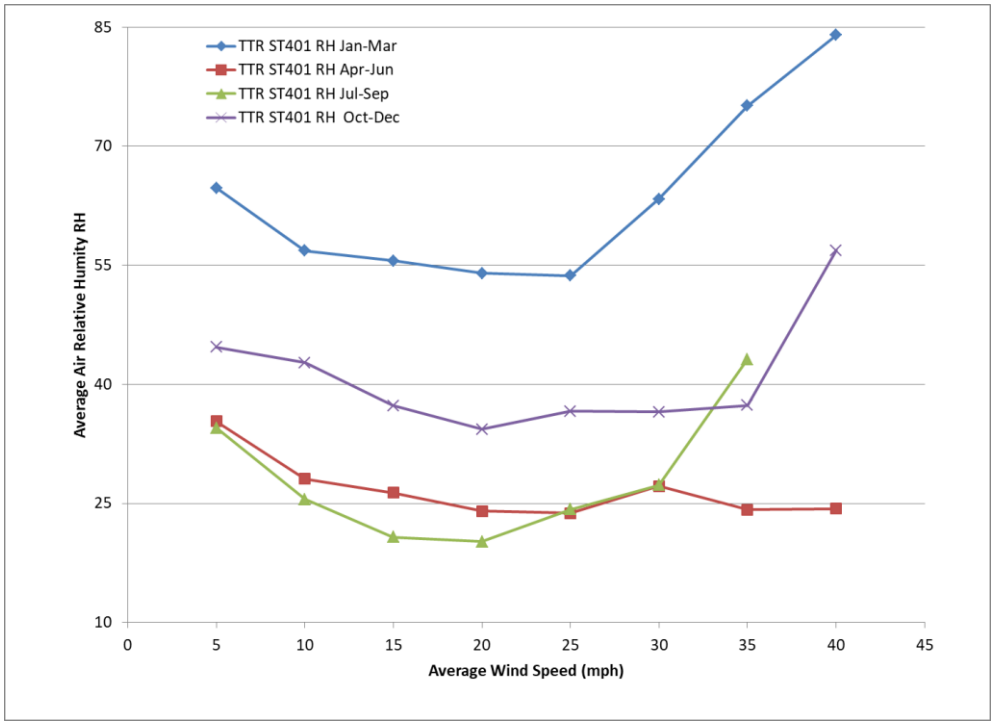

Figure C-57. Relationship between relative humidity and average wind speed, presented by quarter, for Station 401 for May 2017 to December 2019.

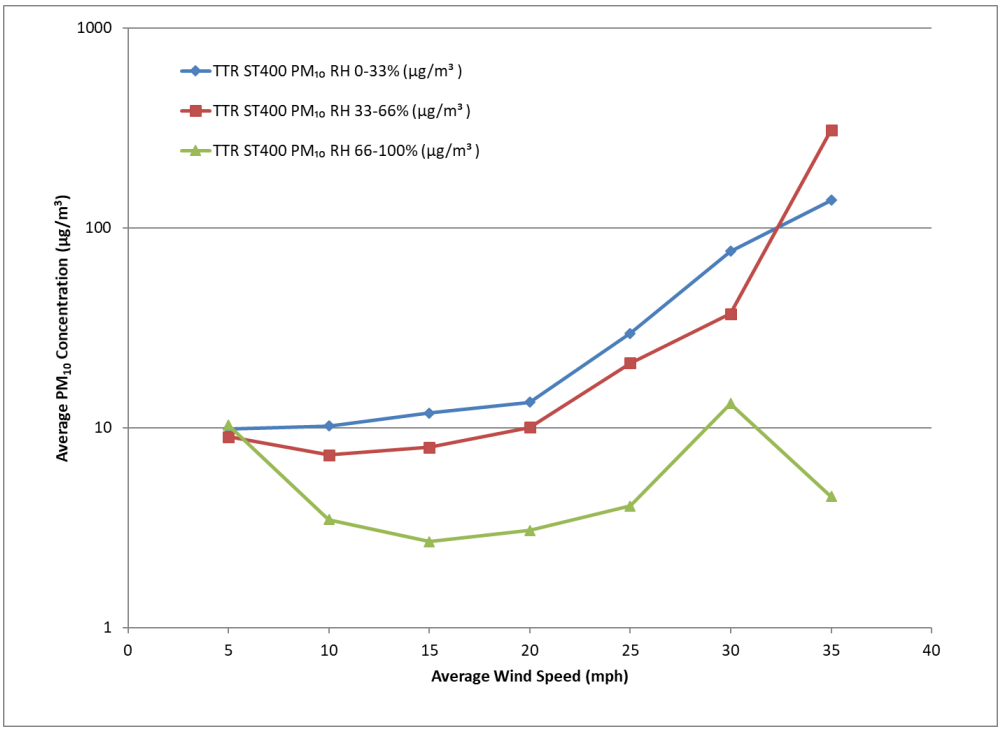

Figure C-58. Relative humidity effect on PM_{10} relationship with average wind speed for Station 400 for May 2017 to December 2019.

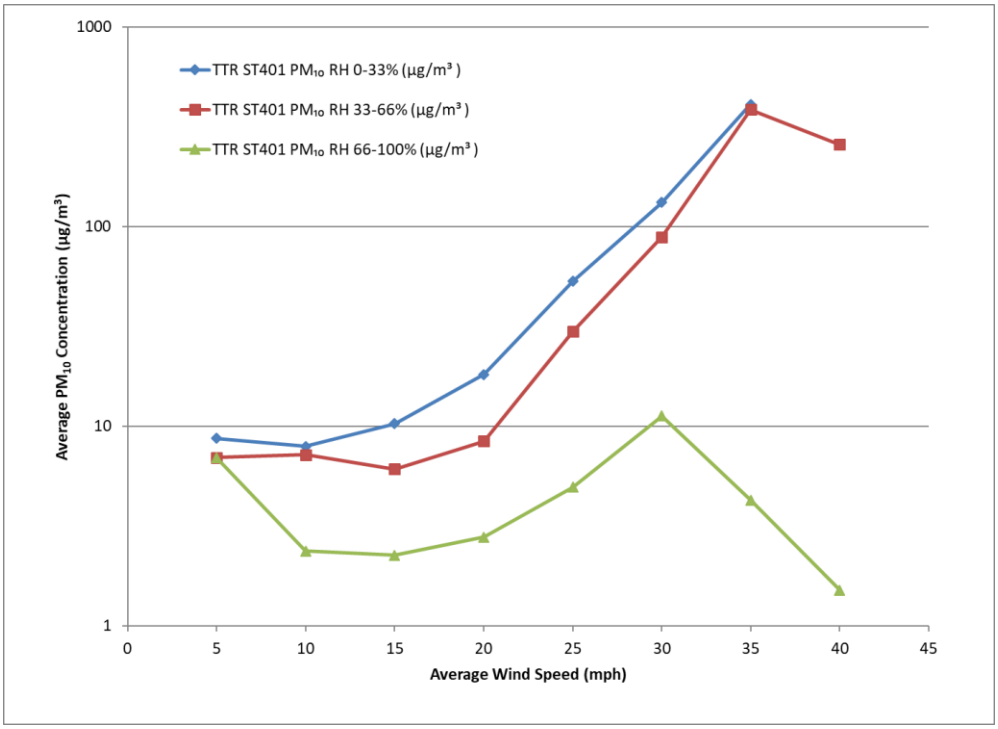

Figure C-59. Relative humidity effect on PM_{10} relationship with average wind speed for Station 401 for May 2017 to December 2019.

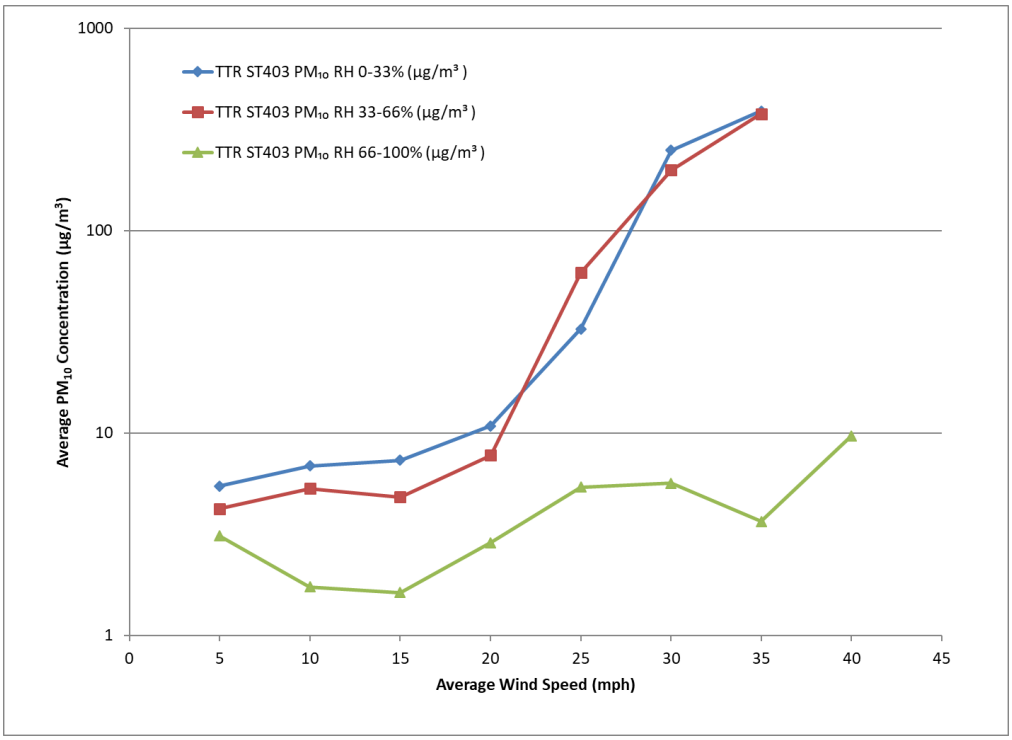

Figure C-60. Relative humidity effect on PM_{10} relationship with average wind speed for Station 403 for May 2017 to December 2019.

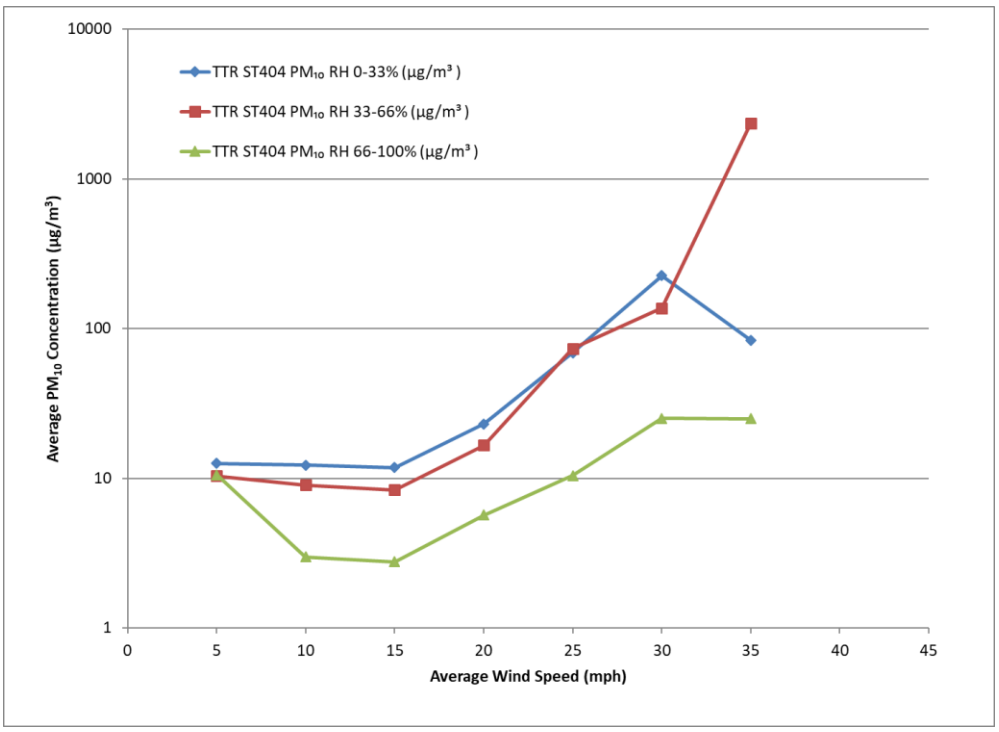

Figure C-61. Relative humidity effect on PM_{10} relationship with average wind speed for Station 404 for May 2017 to December 2019.

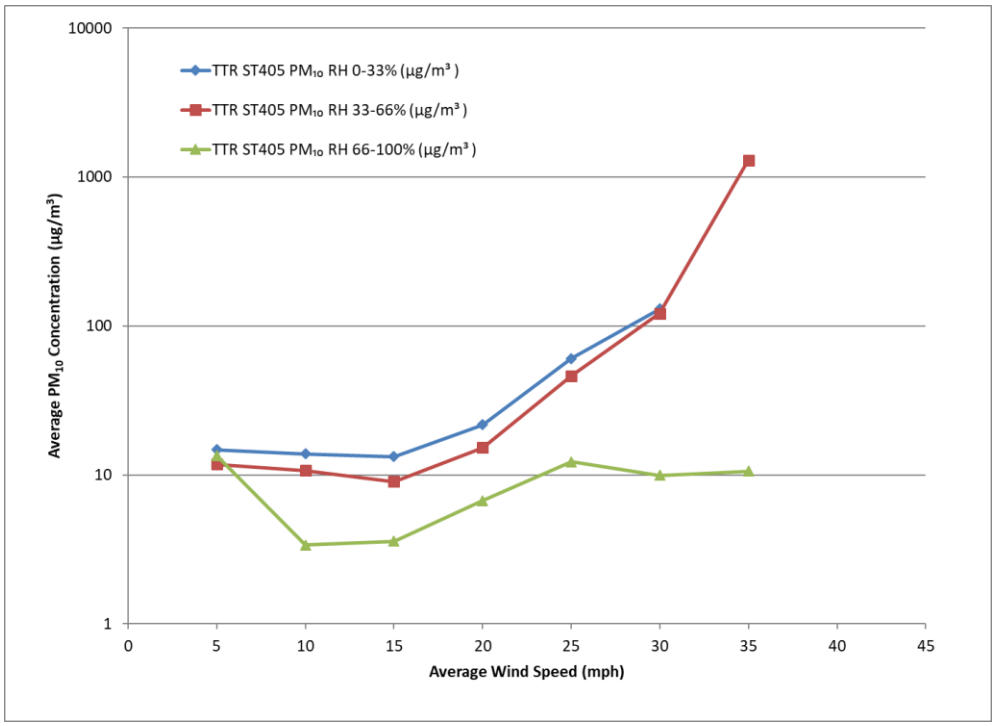

Figure C-62. Relative humidity effect on PM_{10} relationship with average wind speed for Station 405 for May 2017 to December 2019.

Radionuclide Transport

The radiologic content of wind-transported material is assessed by analysis of suspended dust captured on air filters of continuous, low-flow air samplers, and of particles that saltate into passive traps at ground level. Alpha spectroscopy analyses routinely identified $^{239+240}$Pu and ^{241}Am in the saltation samples, and sometimes also found ^{238}Pu. Smaller particle material had higher concentrations than larger particles. Radionuclides enter the saltation traps from multiple directions, not only when the passive sample opening is directed toward the contamination area, which suggests that low-level contaminated material is dispersed outside the fenced area.

In the absence of ground-disturbing activities, gross alpha activities for the suspended dust on the air filters are consistent with regional background (as inferred from concentrations measured by the Community Environmental Monitoring Program), but the more sensitive alpha spectroscopy analyses performed for a limited number of samples often identified $^{239+240}$Pu on the air filters collected from the Clean Slate stations and less commonly ^{238}Pu. Plutonium concentrations were highest at Clean Slate II Station 404 and Clean Slate III Station 401. Both of these stations are located north to northwest, and closer, to the contamination areas than the other station at each site (Figure C-63). Stations 401 and 404 are downwind of the contamination areas during winds from the south. Neither radionuclide was ever detected on filters collected at Station 400, at the Range Operation Center.

Ground disturbance during remediation activities at Clean Slate III (October 2017 through July 2018) and Clean Slate II (September 2018 through August 2019) were strongly associated with increased concentrations of radionuclides in suspended dust. Although the alpha spectroscopy concentrations of $^{239+240}$Pu and ^{238}Pu increased dramatically, these analytical results are not available for every filter, whereas the gross alpha analyses provide a more continuous record. The period from May 2017 to September 2017 when no ground-disturbing activities were occurring at any of the sites shows relatively low gross alpha readings and good agreement between individual stations on filter samples that were collected over each two-week period (Figure C-64). With the beginning of remediation activities at Clean Slate II in October 2017 (indicated by the leftmost blue vertical line on Figure C-64), Stations 404 and 405 exhibit significantly higher gross alpha readings compared with the other stations. As a result of the higher frequency of strong winds from the south (see Figure C-46 and C-47), Station 404 registers higher contaminant concentrations compared with Station 405. Station 404 is also closer to the Clean Slate II contamination area than Station 405. The gross alpha measurements within several months after the completion of ground-disturbance activity (late July 2018) returned to close to the concentrations measured prior to the activity.

Remediation activity occurred at Clean Slate III between September 2018 and August 2019 (yellow vertical lines in Figure C-64). Elevated gross alpha readings were measured during this time at Stations 401 and 403, located north and southeast of the Clean Slate III site. Because of the higher frequency of high sustained winds from the south and the closer location to Clean Slate III, Station 401 has more frequent and higher concentrations of elevated gross alpha readings compared with Station 404. Subsequent to the completion of remediation, concentrations of gross alpha have declined to background levels. Individual transport events detected by the monitoring stations during remediation periods are evaluated in detail in the 2017, 2018, and 2019 annual monitoring reports (see references listed in Appendix A).

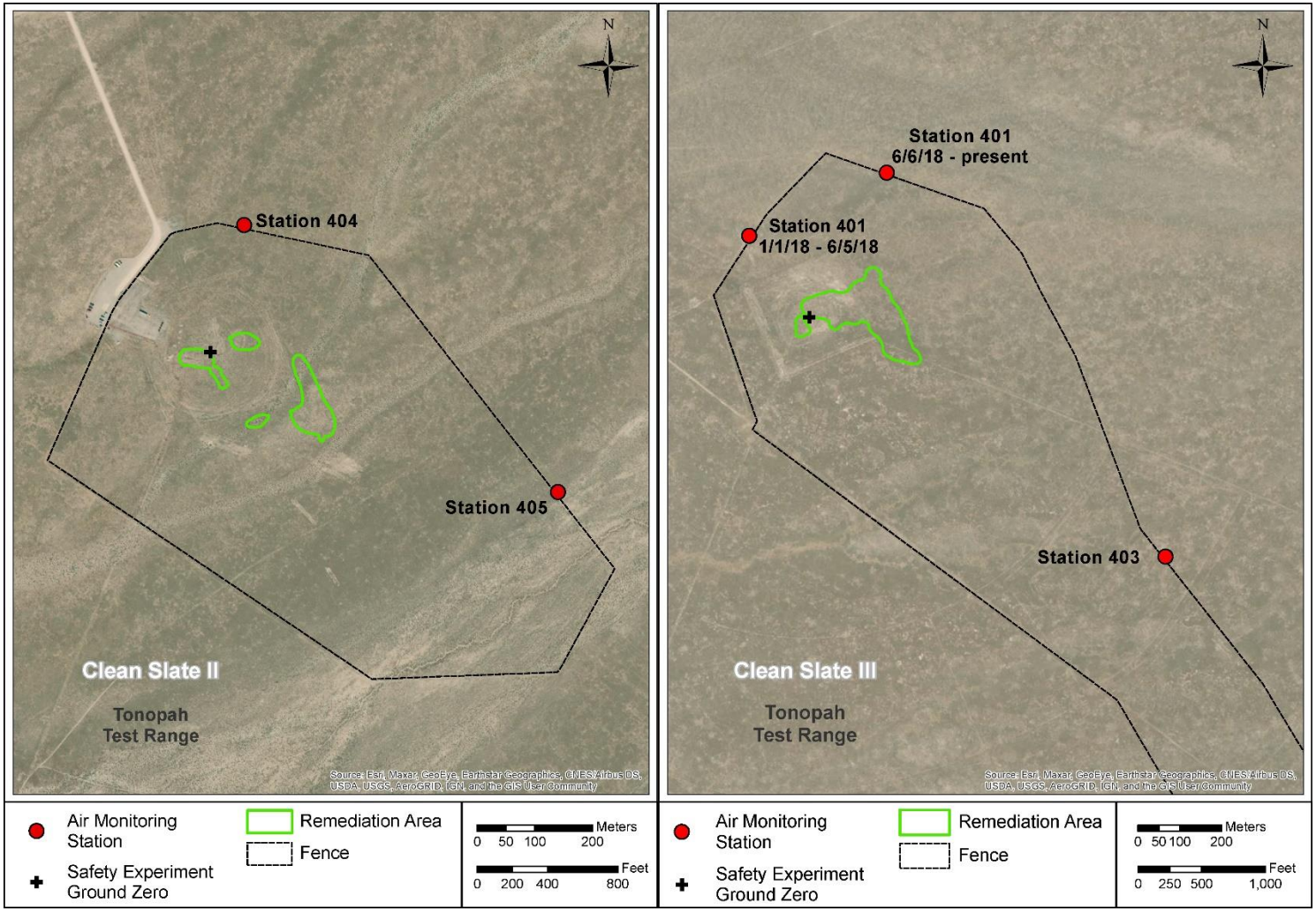

Figure C-63. Locations of the Clean Slate II and III monitoring stations relative to the areas remediated during 2017 through 2019. Station 401 was moved slightly to the east to facilitate remediation activities in mid-2018.

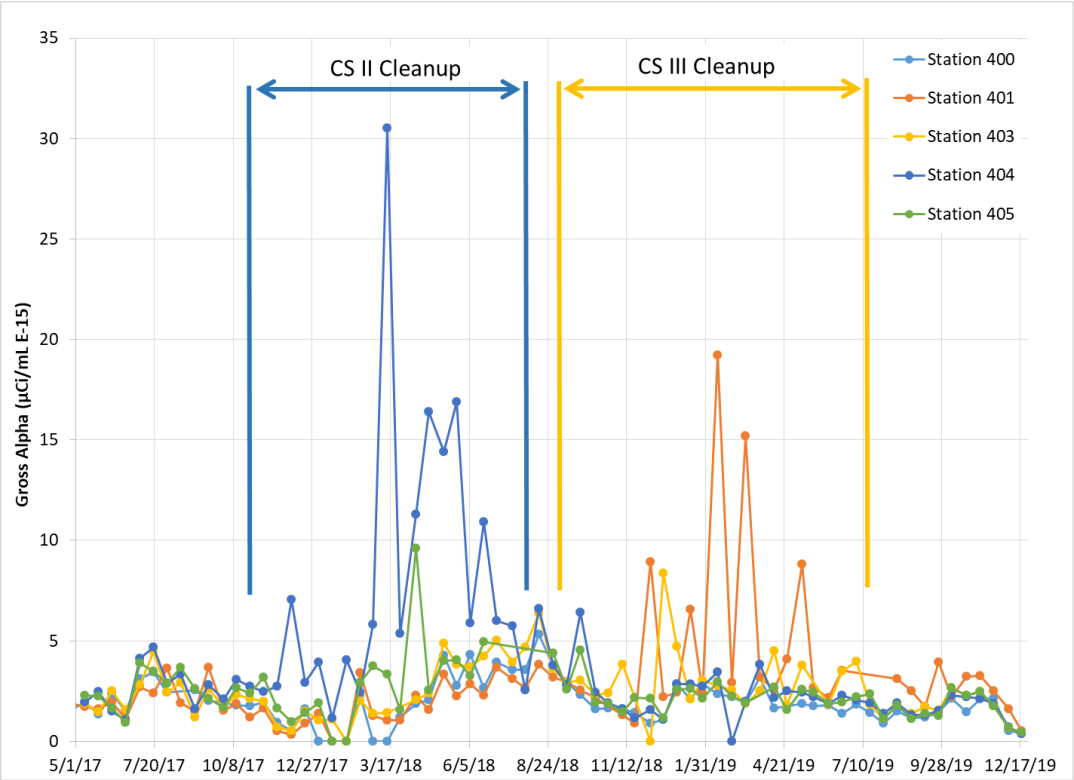

Figure C-64. Time series of gross alpha concentrations for air samples from the Clean Slate monitoring stations.

APPENDIX D. STREAMFLOW FREQUENCY AT THE NEVADA NATIONAL SECURITY SITE, TONOPAH TEST RANGE, AND PROJECT 57 SITE

Prepared by Susan Stillman

Radionuclide contaminated soils can be transported via streamflow. Streamflow values greater than approximately 3 fps have the potential to transport significant amounts of fine sediment downstream (Garcia [ed.], 2008), but some sediment can be transported with low volumes of streamflow. This appendix analyzes the historical frequency of streamflow at the Nevada National Security Site (NNSS), Tonopah Test Range (TTR), and Project 57, as well as addresses projected changes in streamflow frequency by the end of the twenty-first century.

NNSS

The precipitation gages at the monitored Soils Activity sites do not have a sufficiently long period of record to determine the climatology of streamflow frequency. However, there are two National Oceanic and Atmospheric Administration, Special Operations Research Division (SORD) (https://www.sord.nv.doe.gov/) rain gages (UCC and PHS) within 10 km of Plutonium Valley and the Smoky Site, which recorded precipitation from 1959-2011 and 1964-2011, respectively (Figure D-1). To analyze historical streamflow frequency, precipitation thresholds likely to generate streamflow >0 fps and >3 fps are determined based on short-term NNSS precipitation and streamflow records, and the frequency with which the SORD stations exceed these thresholds is evaluated as the historical streamflow frequency.

The precipitation threshold for runoff generation is seasonal. Monsoon season (July through September) precipitation is generally characterized as short intense bursts of rain, and precipitation during the rest of the year (October through June) is generally less intense and more prolonged. Intense rainfall tends to become mostly runoff because the soil cannot absorb precipitation at the rate it is falling. Daily precipitation thresholds of 0.03 in/day and 0.9 in/day are defined as thresholds that usually (>50 percent of days) generate runoff greater than 0 fps and 3 fps, respectively (Figure D-2). The mechanism dominating runoff outside of the monsoon season is “saturation excess,” or runoff that occurs when soil pore space becomes filled and cannot absorb any more water. Runoff thresholds for this mechanism are more difficult to obtain because they are closely tied to antecedent soil moisture conditions. Nonetheless, a daily precipitation threshold for runoff generation is defined as 0.2 in/day, which is the daily precipitation amount above which runoff occurred 50 percent of the time (Figure D-3). Streamflow never exceeded 3 fps outside of the monsoon season at the Smoky Site, and therefore a precipitation threshold for streamflow exceeding 3 fps during October through June cannot be identified. There were not sufficient streamflow data at Plutonium Valley to derive similar thresholds at that site. However, as a first-order approximation, the same thresholds are also applied to Plutonium Valley.

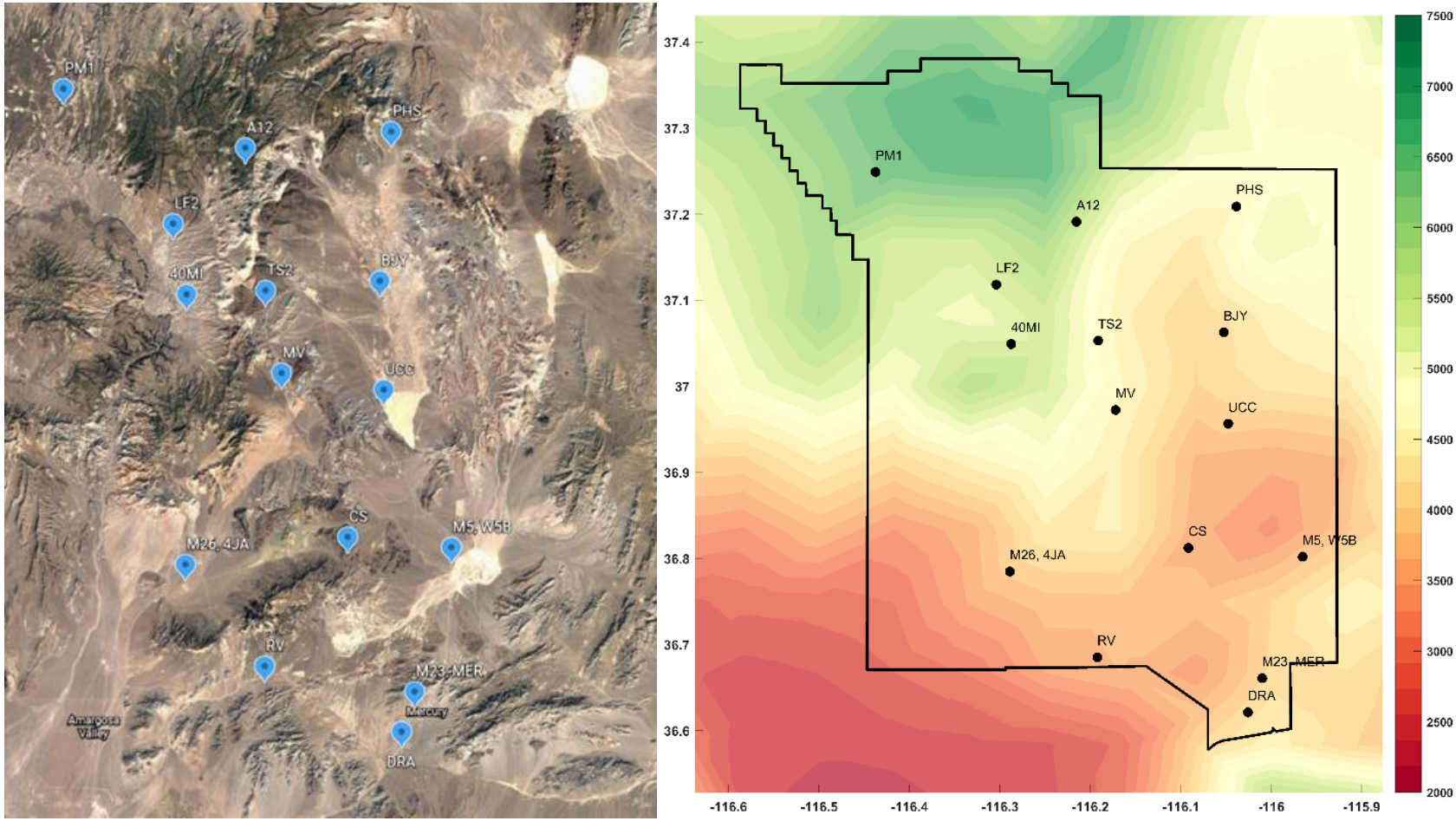

Figure D-1. Location of SORD rain gages on the NNSS with at least 30 years of data overlaid on visual imagery (left) and a 5 km resolution digital elevation model (right). The Smoky Site and Plutonium Valley are near SORD gages UCC and PHS, respectively.

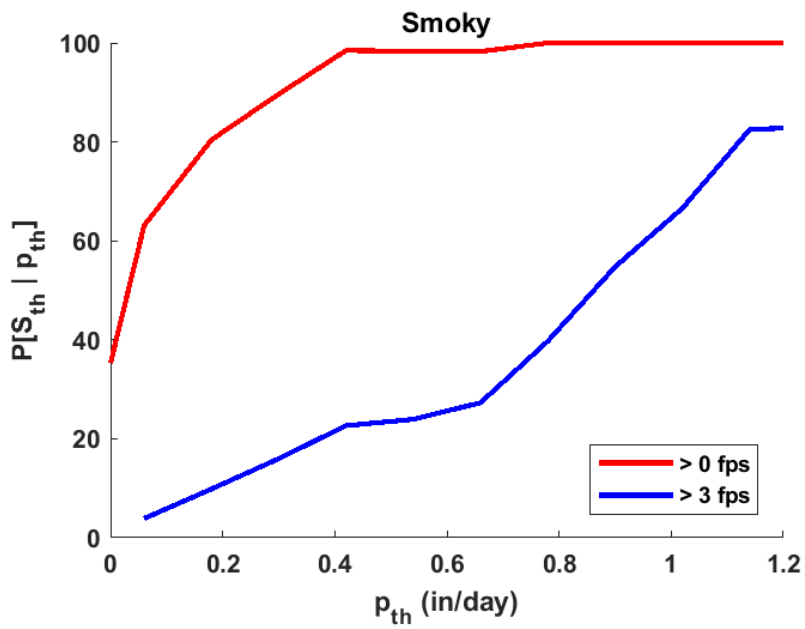

Figure D-2. Probability of streamflow exceeding 0 fps (red) and exceeding 3 fps (blue) for daily precipitation amounts exceeding the values on the x-axis during July through September at the Smoky Site.

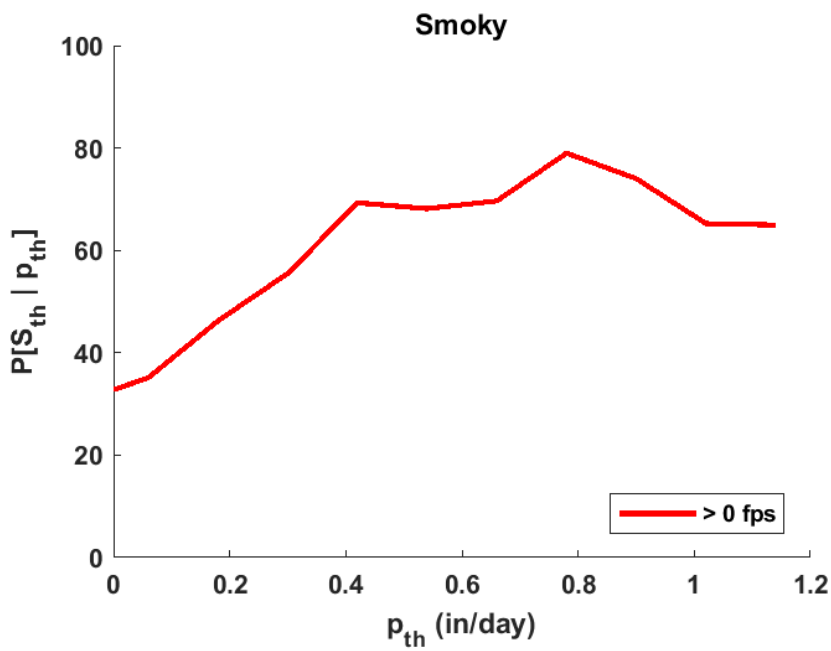

Figure D-3. Probability of streamflow exceeding 0 fps for daily precipitation amounts exceeding the values on the x-axis during October through June at the Smoky Site. Note: streamflow never exceeded 3 fps outside of July through September during the Smoky Site gage records.

During the NNSS gage record time frame, precipitation exceeding the threshold for runoff generation occurred slightly more frequently during July through September than during the rest of the year combined (Table D-1). Threshold exceedance is evaluated at the two SORD gages near the Smoky Site and Plutonium Valley. Over their respective periods of record, the two SORD gages recorded precipitation exceeding 0.03 in/day 50 to 60 times per decade (Figure D-4) and exceeded 0.9 in/day 3 to 4 times per decade (Figure D-5) during July through September. Precipitation exceeding 0.2 in/day during October through June occurred 70 to 85 times per decade (Figure D-6). Because these thresholds result in runoff 50 percent of the time, these results suggest that **streamflow exceeding 0 fps likely occurred approximately 60 to 70 times per decade and streamflow exceeding 3 fps likely occurred just 1 or 2 times per decade between 1959 and 2011 at the NNSS**. This is consistent with streamflow at the Smoky Site, where streamflow exceeding 0 fps occurred 57 times and streamflow exceeding 3 fps occurred three times between 2011 and 2018.

Although precipitation thresholds for runoff generation are spatially variable and depend on, among other things, soil properties, slope, and vegetation, the only streamflow available for this analysis is at the Smoky Site. Therefore, as a first-order approximation, thresholds determined for the Smoky Site are used across the NNSS. The 15 SORD rain gages with at least 30 years of data throughout the NNSS are used (several gages were replaced with new ones and their records were combined to create long-term time series). Figures D-7 and D-8 show the number of times each year the abovementioned thresholds were exceeded at each SORD gage. Precipitation exceeding 0.03 in/day occurs more frequently at higher elevation gages than lower elevation gages during July through September. Additionally, precipitation exceeding 0.2 in/day occurs more frequently at higher elevation gages than lower elevation gages during October through June. This suggests that streamflow occurs more frequently at higher elevations than lower elevations at the NNSS. Regions with more uneven terrain are also likely to generate streamflow more frequently and with higher intensity than flatter areas.

Table D-1. NNSS site information: site name, period of available data, number of days with missing values, number of years of data ([# days with data]/365), number of days during July through September with precipitation exceeding 0.03 in/day, number of days during July through September with precipitation exceeding 0.9 in/day, and number of days during October through June with precipitation exceeding 0.2 in/day.

Site	Date Range	Missing days	# years	J-S >0.03	J-S >0.9	O-J >0.2
PV1	Jul 20, 2012 – Sep 30, 2018	4	6.2	39	2	35
PV2	Aug 26, 2011 – Sep 30, 2018	14	7.1	38	1	34
Smoky	Jul 15, 2011 – Sep 30, 2018	3	7.2	58	4	32

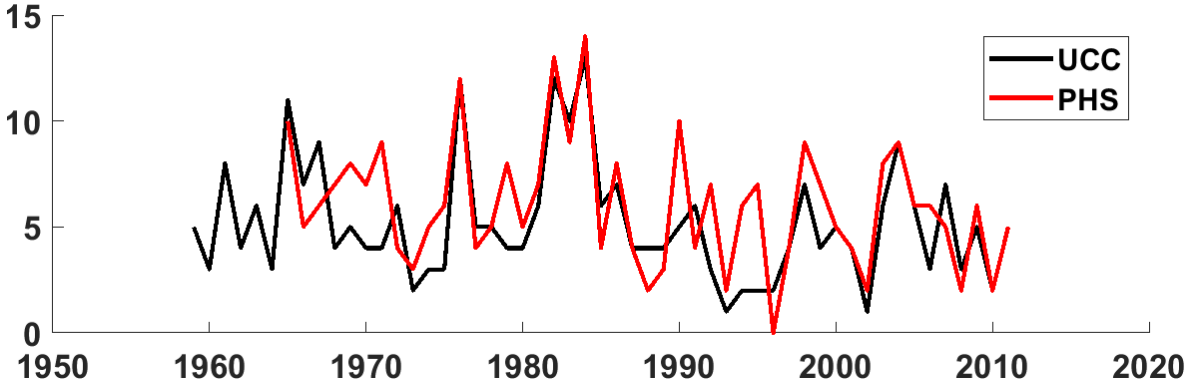

Figure D-4. Number of days per year during July through September with precipitation exceeding 0.03 in/day at two SORD sites near Plutonium Valley and the Smoky Site (UCC and PHS, respectively).

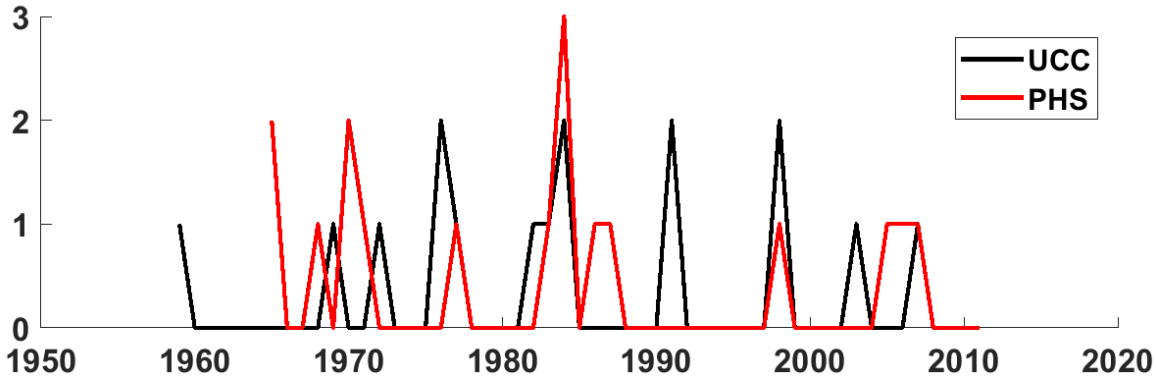

Figure D-5. Number of days per year during July through September with precipitation exceeding 0.9 in/day at two SORD sites near Plutonium Valley and the Smoky Site (UCC and PHS, respectively).

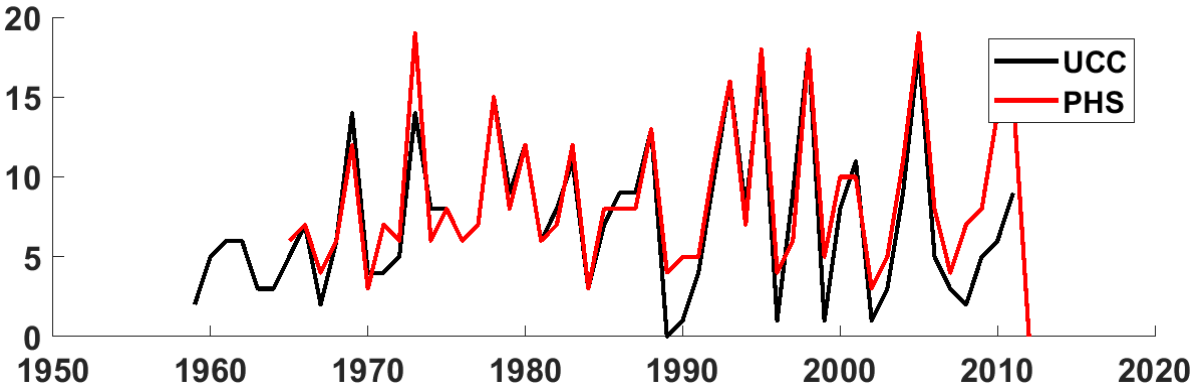

Figure D-6. Number of days per year during October through June with precipitation exceeding 0.2 in/day at two SORD sites near Plutonium Valley and the Smoky Site (UCC and PHS, respectively).

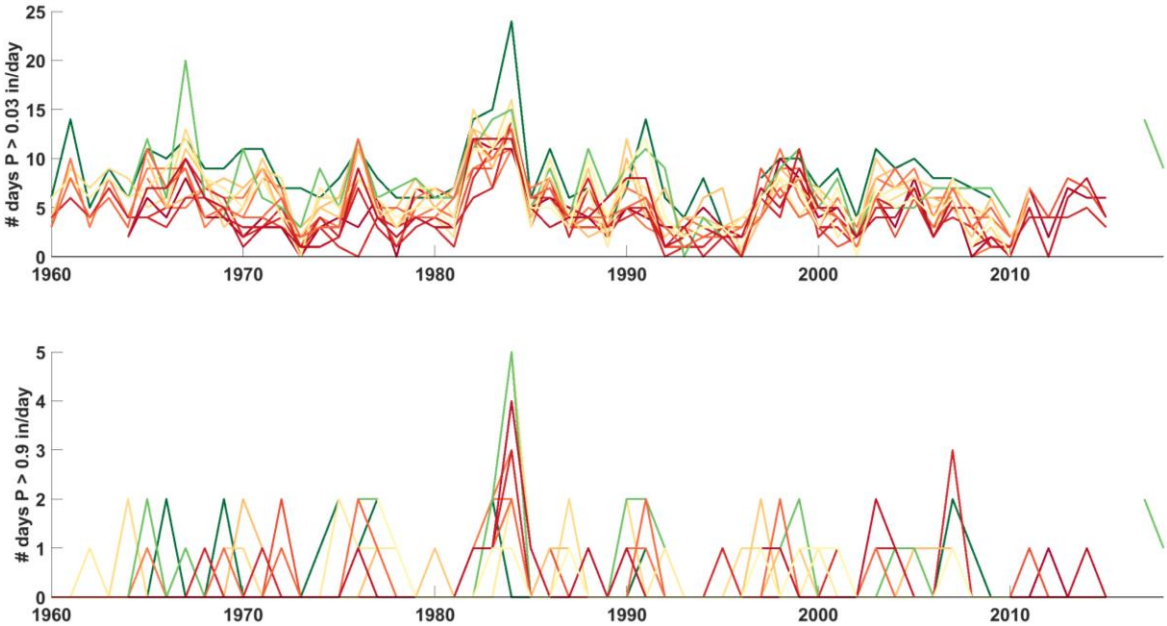

Figure D-7. Number of days per year with precipitation exceeding 0.03 in/day (top) and 0.9 in/day (bottom) during July through September at each of the 15 NNSS SORD gages. Each line represents one SORD gage and colors range from the lowest elevation gage (red) to the highest elevation gage (green).

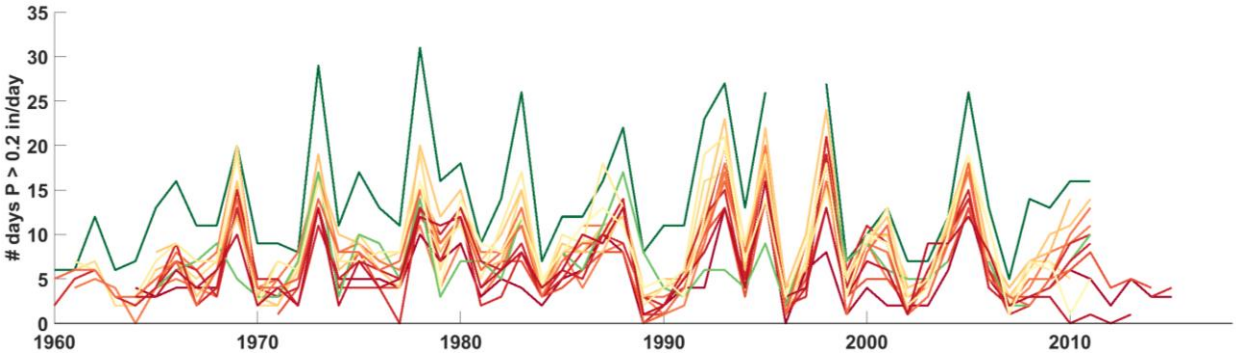

Figure D-8. Number of days per year with precipitation exceeding 0.2 in/day (bottom) during October through June at each of the 15 NNSS SORD gages. Each line represents one SORD gage and colors range from the lowest elevation gage (red) to the highest elevation gage (green).

At each of the SORD gages, precipitation exceeded 0.03 in/day between 40 and 80 times per decade and exceeded 0.9 in/day between 1 and 7 times per decade during July through September (Figure D-9). Precipitation exceeded 0.2 in/day between 50 and 140 times per decade at each of the SORD gages during October through June (Figure D-10).

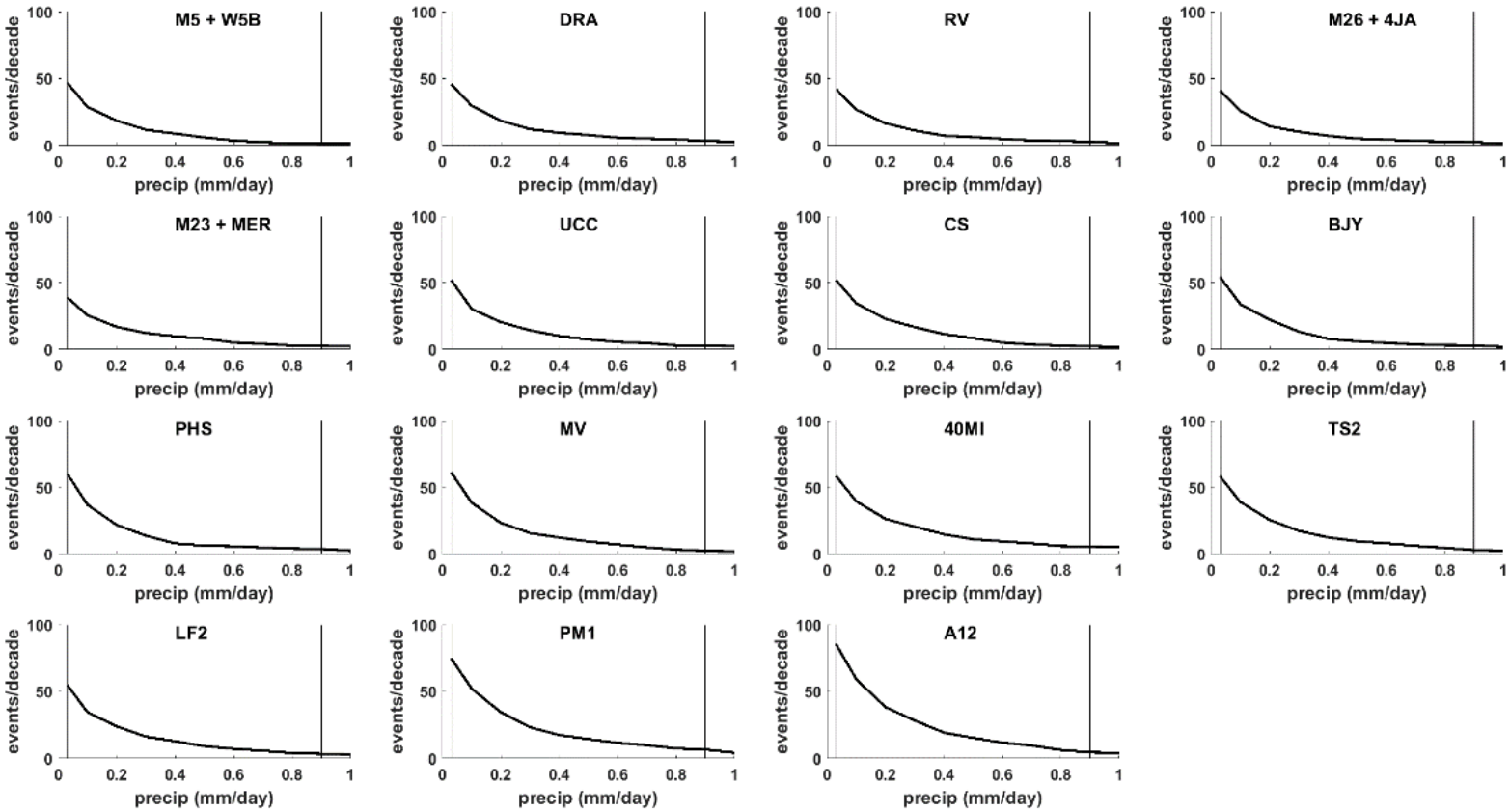

Figure D-9. Average number of days per decade with precipitation exceeding the value on the x-axis during July through September at each of the 15 NNSS SORD gages. Vertical lines represent the precipitation thresholds of 0.03 in/day and 0.9 in/day.

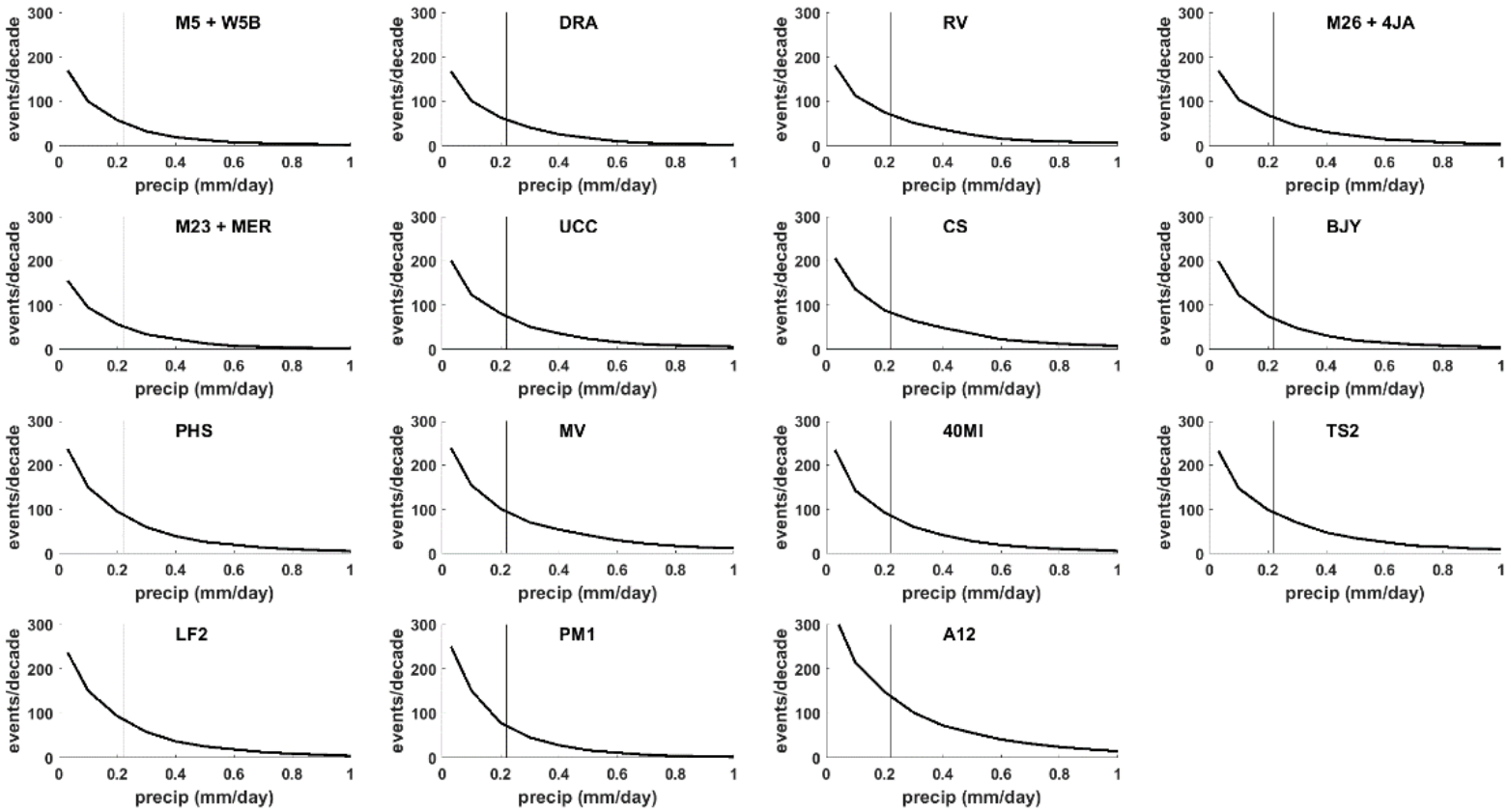

Figure D-10. Average number of days per decade with precipitation exceeding the value on the x-axis during October through June at each of the 15 NNSS SORD gages. Vertical lines represent the precipitation threshold of 0.2 in/day.

The downscaled global climate models (dGCMs) discussed below indicate that by the end of the twenty-first century, precipitation is expected to increase during the monsoon season. In terms of the nonmonsoon period, an expected increase in precipitation during winter is offset by projections of less precipitation during spring and fall. The strongest changes are expected to be at the higher elevation sites. Future changes in frequency of streamflow are assessed using the multimodel mean of a suite of 25 dGCMs from the fifth generation Coupled Model Intercomparison Project, downscaled using the Multivariate Adaptive Constructed Analogs method (Abatzoglou and Brown, 2011). The historical dGCM runs showed between 70 and 80 events per decade exceeding 0.03 in/day and approximately one event per decade exceeding 0.9 in/day at each of the Smoky Site and Plutonium Valley sites during July through September (Figure D-11). The dGCMs predict that by the end of the century, precipitation will exceed 0.03 in/day approximately 15 more times per decade, or an increase of approximately 15 percent during July through September. Precipitation exceeding 0.9 in/day is expected to occur more frequently than it historically occurred by up to one event per decade, or a nearly 100 percent increase from the SORD record (Figure D-12). Precipitation exceeding 0.2 in/day is expected to decrease by one or two events per decade (Figure D-13). Overall, these results suggest an **increase in streamflow events by 6 to 7 events per decade, or a 10 percent increase from the SORD record, and a slight increase in streamflow exceeding 3 fps by less than 0.5 events per decade, or a 25-50 percent increase from the SORD record, by the end of the twenty-first century.**

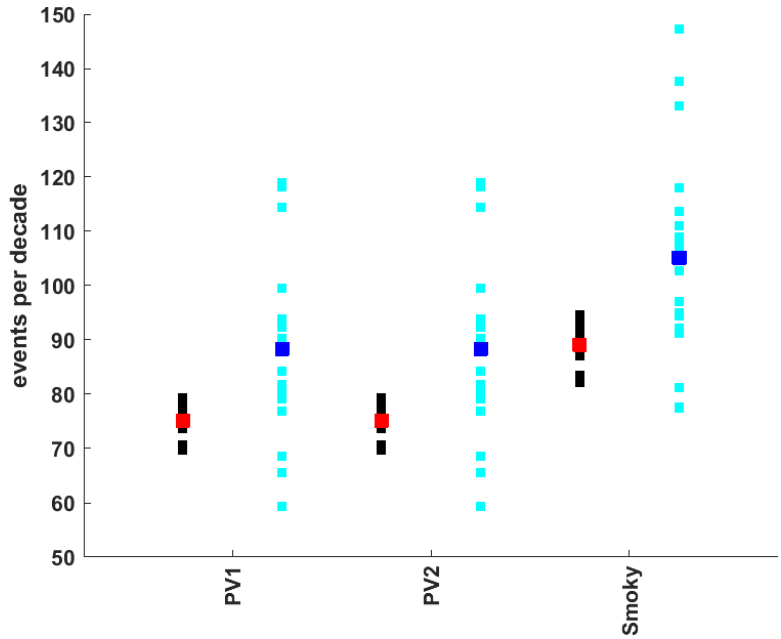

Figure D-11. Frequency (events per decade) that daily precipitation exceeds 0.03 inch at each Plutonium Valley and Smoky Site rain gage during July through September. The black boxes represent each of the 18 climate models from 1951-2000, the red boxes are the multimodel mean from 1951-2000 (mean of black boxes), the light-blue boxes represent each of the 18 climate models from 2051-2100, and the dark-blue boxes represent the multimodel mean from 2051-2100 (mean of light-blue boxes).

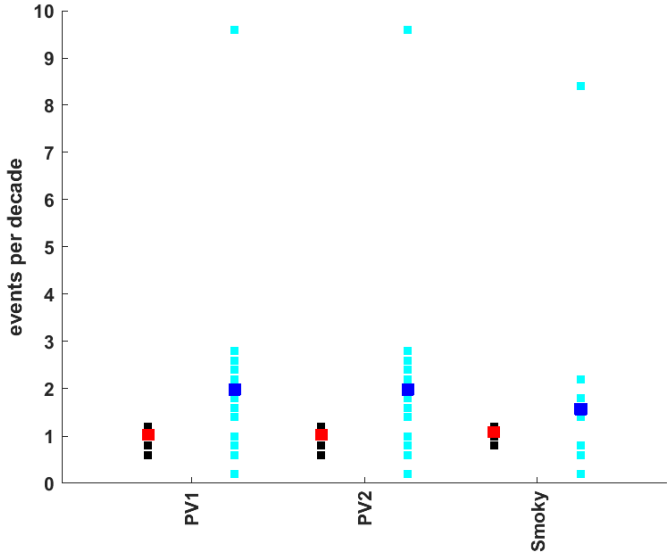

Figure D-12. Frequency (events per decade) that daily precipitation exceeds 0.9 inch at each Plutonium Valley and Smoky Site rain gage during July through September. The black boxes represent each of the 18 climate models from 1951-2000, the red boxes are the multimodel mean from 1951-2000 (mean of black boxes), the light-blue boxes represent each of the 18 climate models from 2051-2100, and the dark-blue boxes represent the multimodel mean from 2051-2100 (mean of light-blue boxes).

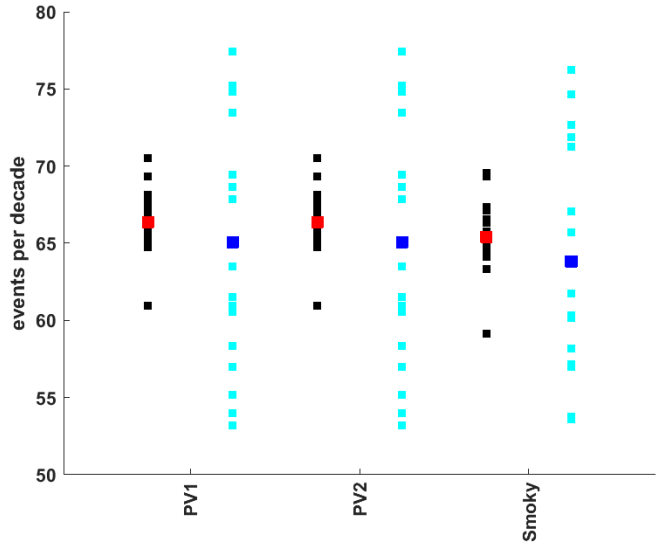

Figure D-13. Frequency (events per decade) that daily precipitation exceeds 0.22 inch at each Plutonium Valley and Smoky Site rain gage during October through June (nonmonsoon). The black boxes represent each of the 18 climate models from 1951 through 2000, the red boxes are the multimodel mean from 1951-2000 (mean of black boxes), the light-blue boxes represent each of the 18 climate models from 2051-2100, and the dark-blue boxes represent the multimodel mean from 2051-2100 (mean of light-blue boxes).

It should be noted that in a warming climate, soils are likely to become drier and the derived threshold for saturation excess runoff may increase. However, a sensitivity test is performed using October through June precipitation thresholds between 0.2 and 1 in/day, resulting in changes between -1 and 1 events per decade, which is small compared with the frequency change in monsoon precipitation events. Future changes in streamflow frequency are therefore expected to be dominated by monsoon precipitation changes.

TTR

The precipitation threshold likely to produce sediment transport may be different at TTR than at the Smoky Site. However, streamflow data are not available for TTR, and therefore the same daily precipitation thresholds for streamflow, >0 fps and >3 fps, are applied to the TTR and nearby gages as a first-order approximation. There are not sufficient precipitation data to generate a climatology of precipitation exceeding 0.9 in/day at any of the TTR gages, but Table D-2 describes the recorded exceedance information. There is one National Climate Data Center (NCDC) rain gage in the town of Tonopah, Nevada, and one at the Tonopah airport, which are the closest long-term precipitation records to TTR. The two NCDC gages in Tonopah are 13 km apart and approximately 55 km from TTR. The Tonopah gage has data from 1928-1954, 1986-2000, and 2011-2016, and the Tonopah airport gage has data from 1954-2016. Although combining the two gages would provide a continuous precipitation record from 1928-2016, they should not be combined because the precipitation recorded during the overlapping periods of 1986-2000 and 2011-2016 are too dissimilar, with a correlation of just 0.48.

During the TTR gage record, precipitation exceeding runoff-generating thresholds occurred predominantly during July through September. Over the respective periods of record at the NCDC stations nearest TTR, precipitation exceeded 0.03 in/day 55 to 70 times per decade (Figure D-14) and exceeded 0.9 in/day 2 to 3 times per decade (Figure D-15) during July through September. Precipitation exceeding 0.2 in/day during October through June occurred 50 to 60 times per decade (Figure D-16). These results suggest that **streamflow exceeding 0 fps likely occurred approximately 55 to 65 times per decade and streamflow exceeding 3 fps like occurred just over one time per decade between 1928 and 2017 at TTR.**

Table D-2. TTR site information: site name, period of available data, number of days with missing values, number of years of data ([# days with data]/365), number of days during July through September with precipitation exceeding 0.03 in/day, number of days during July through September with precipitation exceeding 0.9 in/day, and number of days during October through June with precipitation exceeding 0.2 in/day.

Site	Date Range	Missing days	# years	J-S >0.03	J-S >0.9	O-J >0.2
TTR400	Jan 1, 2009 – Jul 31,2018	10	9.6	61	1	33
TTR401	Dec 23, 2009 – Jul 31, 2018	27	8.5	69	3	29
TTR402	May 19 2011 – Apr 24, 2017	47	5.8	45	4	22
TTR403	Apr 26, 2017 – Jul 31, 2018	55	1.2	21	0	7
TTR404	Apr 26, 2017 – Aug 31, 2018	48	1.3	25	0	2
TTR405	Apr 26, 2017 – Aug 31, 2018	47	1.4	25	1	2

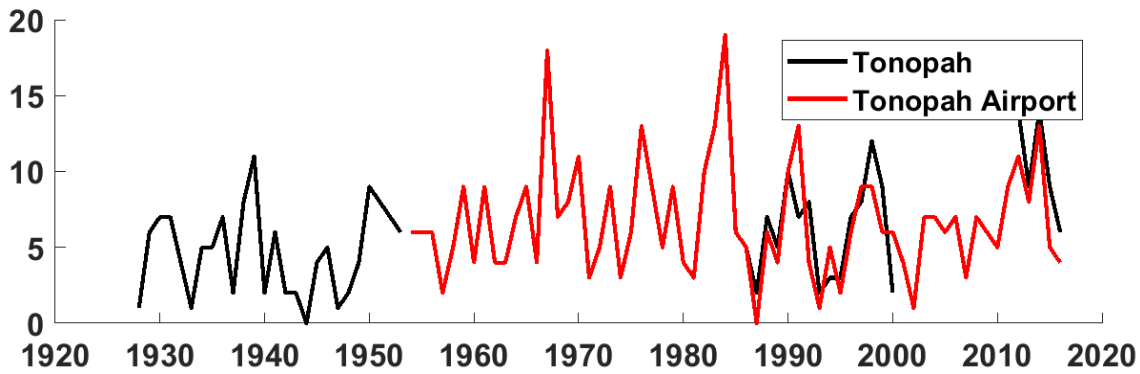

Figure D-14. Number of days per year during July through September with precipitation exceeding 0.03 in/day at two NCDC stations near TTR.

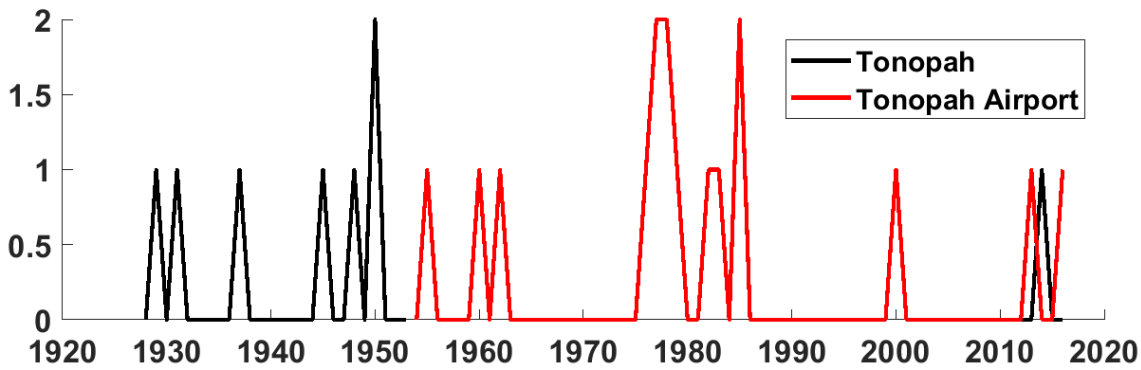

Figure D-15. Number of days per year during July through September with precipitation exceeding 0.9 in/day at two NCDC stations near TTR.

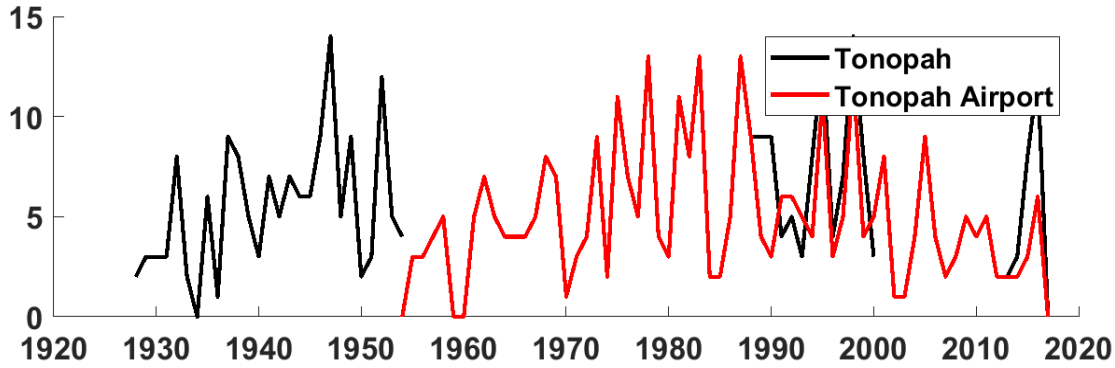

Figure D-16. Number of days per year during October through June with precipitation exceeding 0.2 in/day at two NCDC stations near TTR.

Future changes in streamflow frequency are assessed using dGCMs. Historical dGCM precipitation exceeded 0.03 in/day approximately 50 times per decade and exceeded 0.9 in/day approximately once per decade during July through September at TTR. Figure D-17 shows the historical and projected future frequencies of exceeding these thresholds at each of the station locations in TTR. Precipitation exceeding 0.9 in/day is expected to increase in frequency by one to two events per decade during July through September, or a 100 percent to 200 percent increase from the NCDC record. Precipitation exceeding 0.03 in/day is expected to increase in frequency by approximately 18 events per decade during July through September. Precipitation exceeding 0.2 in/day is expected to decrease by approximately one event per decade during October through June. Therefore, **streamflow at TTR is expected to increase in frequency by approximately 9 events per decade, or a 15 percent increase from the NCDC historical record, and streamflow at TTR exceeding 3 fps will likely increase in frequency by 0.5 to 1 events per decade, or a 50-100 percent increase from the NCDC historical record.**

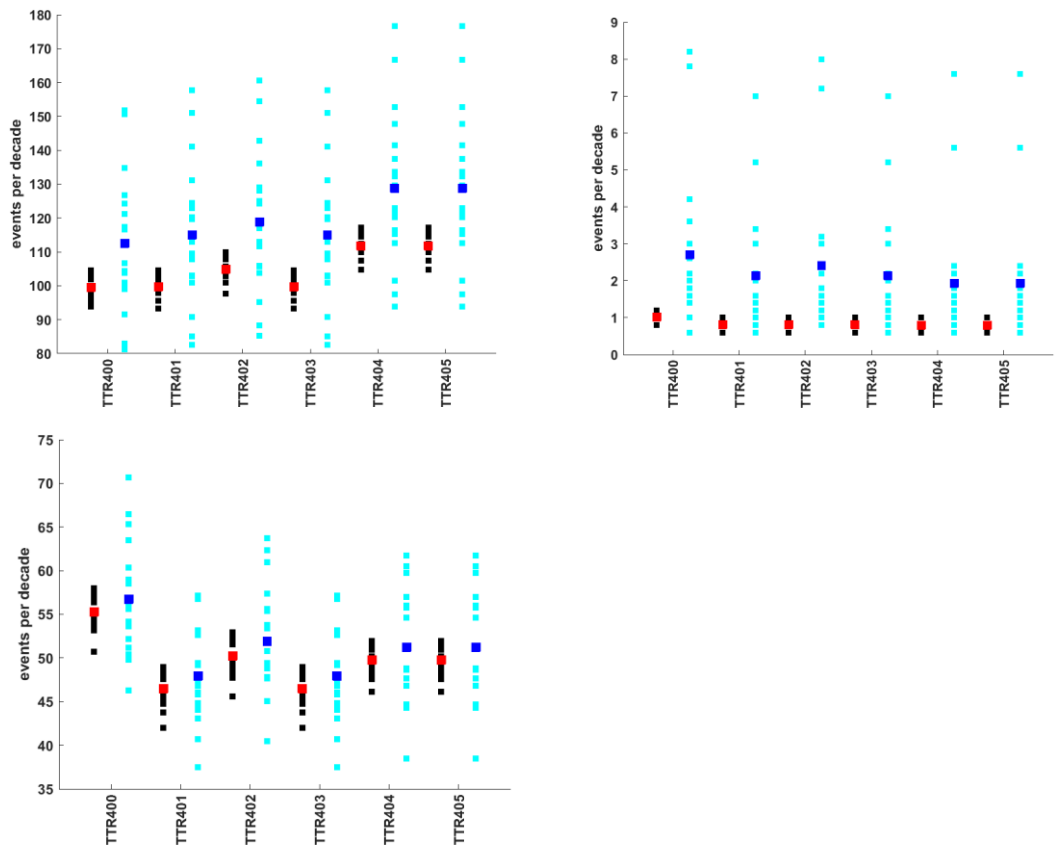

Figure D-17. Frequency (events per decade) that daily precipitation exceeds 0.03 and 0.9 inch at each TTR rain gage during July through September (top left and right, respectively) and frequency that daily precipitation exceeds 0.2 inch at each TTR rain gage during October through June (bottom). The black boxes represent each of 18 climate models from 1951-2000, the red boxes are the multimodel mean from 1951-2000 (mean of black boxes), the light-blue boxes represent each of the 18 climate models from 2051-2100, and the dark-blue boxes represent the multimodel mean from 2051-2100 (mean of light-blue boxes).

PROJECT 57

Precipitation records at Project 57 are just seven years in length, and there are no rain gages near enough to be used as a proxy. Within Project 57, there have been four gage locations. Gages 1 and 3 are approximately collocated, and therefore combined. The same is true for gages 2 and 4. Table D-3 presents the historical exceedance information for the seven years of record.

Table D-3. Project 57 site information: site name, period of available data, number of days with missing values, number of years of data ([# days with data]/365), number of days during July through September with precipitation exceeding 0.03 in/day, number of days during July through September with precipitation exceeding 0.9 in/day, and number of days during October through June with precipitation exceeding 0.2 in/day.

Site	**Date Range**	**Missing days**	**# years**	**J-S >0.03**	**J-S >0.9**	**O-J >0.2**
$P57_{1,3}$	Apr 21, 2011 – Oct 8, 2018	143	7	50	1	36
$P57_{2,4}$	Nov 18, 2011 – Dec 31, 2018	27	7	55	3	34

Despite the lack of gage data near Project 57, future projections of dGCM precipitation exceeding 0.03 in/day and 0.9 in/day during July through September and exceeding 0.2 in/day during October through June are shown in Figure D-18. Precipitation exceeding 0.03 in/day is projected to increase by 18 events per decade during July through September at Project 57 by the end of the twenty-first century. Precipitation exceeding 0.9 in/day is projected to increase by one event per decade during July through September. Precipitation exceeding 0.2 in/day is expected to decrease by one event per decade during October through June. Therefore, **it is expected that by the end of the century, streamflow >0 fps will increase in frequency by 8 to 9 events per decade and streamflow >3 fps will slightly increase in frequency by 0.5 events per decade at Project 57.**

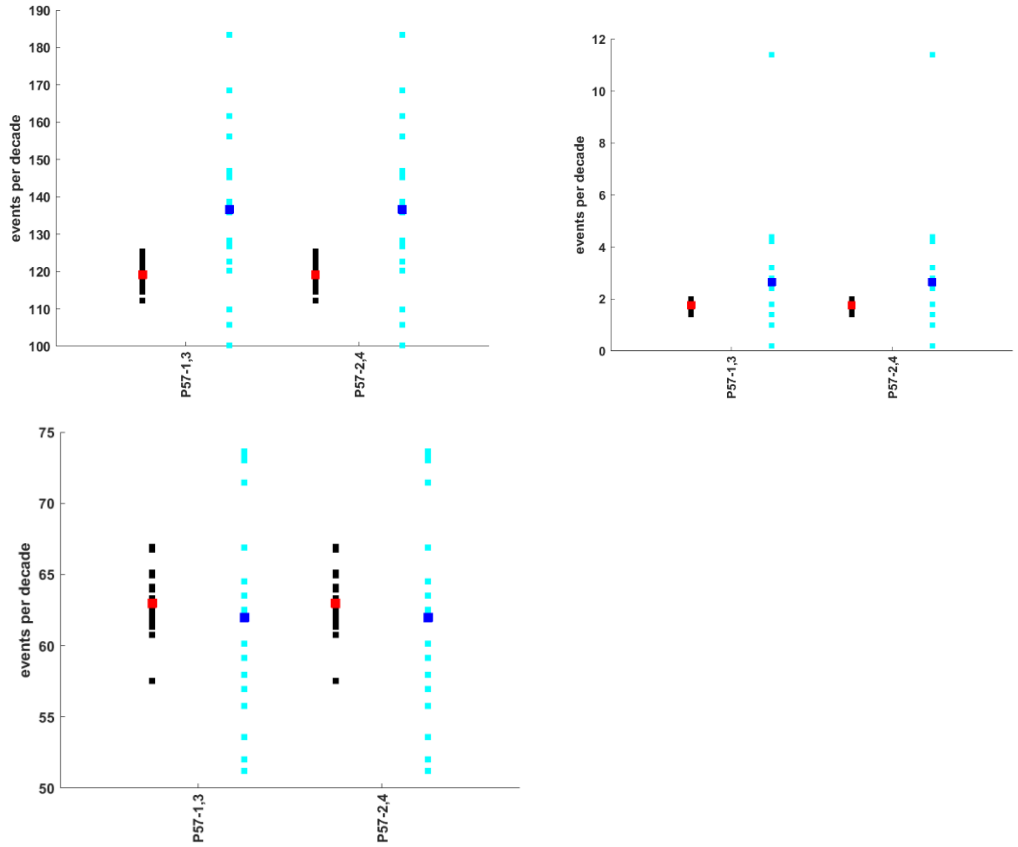

Figure D-18. Frequency (events per decade) that daily precipitation exceeds 0.03 and 0.9 inch at each Project 57 rain gage during July through September (top left and right, respectively) and frequency that daily precipitation exceeds 0.2 inch at each Project 57 rain gage during October through June (bottom). The black boxes represent each of the 18 climate models from 1951-2000, the red boxes are the multimodel mean from 1951-2000 (mean of black boxes), the light-blue boxes represent each of the 18 climate models from 2051-2100, and the dark-blue boxes represent the multimodel mean from 2051-2100 (mean of light-blue boxes).

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Garcia, M. (ed.), 2008. *Sedimentation Engineering: Processes, Measurements, Modeling, and Practices*. American Society of Civil Engineers, ASCE Manuals and Reports on Engineering Practice 110.

APPENDIX E. SMOKY MULTIYEAR CHANNEL BED SAMPLE DATA ANALYSES

Prepared by Steve A. Mizell

An analysis was performed to investigate radiological activity over time within an ephemeral channel crossing the Smoky Site, based on channel bedload samples. The approximate sampling location is identified in relation to the boundaries of the assumed hydraulically "active" portion of the ephemeral channel. Sample locations were selected to represent sites likely to experience deposition of finer-grained materials because of flow in the channel.

The Smoky channel has been sampled on three occasions. The first was on August 15, 2013, following runoff events in July 2013; the second was on August 20, 2014, following runoff events in July and August 2014 (Mizell *et al.*, 2017); and the third was on August 7, 2018, following channel flow on July 14, 2018. Figure E-1 identifies the locations of all samples collected on August 15, 2013, and August 7, 2018. A comparison of multiyear radiological concentrations—assuming particle size fractions less than 63 µm, as well as greater than 63 µm but less than 250 µm—of ^{241}Am, ^{238}Pu, and $^{239+240}$Pu is presented in Figures E-2, E-3, and E-4, respectively. Results of radiological analyses were included in the multiyear comparison (Figures E-2 to E-4) only if the samples were collected in the active channel in order to standardize the data. The exception is the August 20, 2014, sampling campaign for which exact spatial information is unavailable, but Mizell *et al.* (2017) describes that the samples were collected downstream of the flume. Therefore, specific activity results from all sampling locations on August 20, 2014, were included in Figures E-2 to E-4, although it is unknown whether the samples were taken in the active channel. A review of photographs taken during the August 15, 2013, sampling campaign indicate that samples 2, 3, 5, and 7 were collected within the active channel. Channel samples taken near the centerline on August 7, 2018 (samples 3, 6, 8, 9, 10), are included in the multiyear comparison in addition to the four samples from August 2013. The overall increasing trend of isotope specific activity with time is evident in all multiyear comparisons (Figures E-2 to E-4).

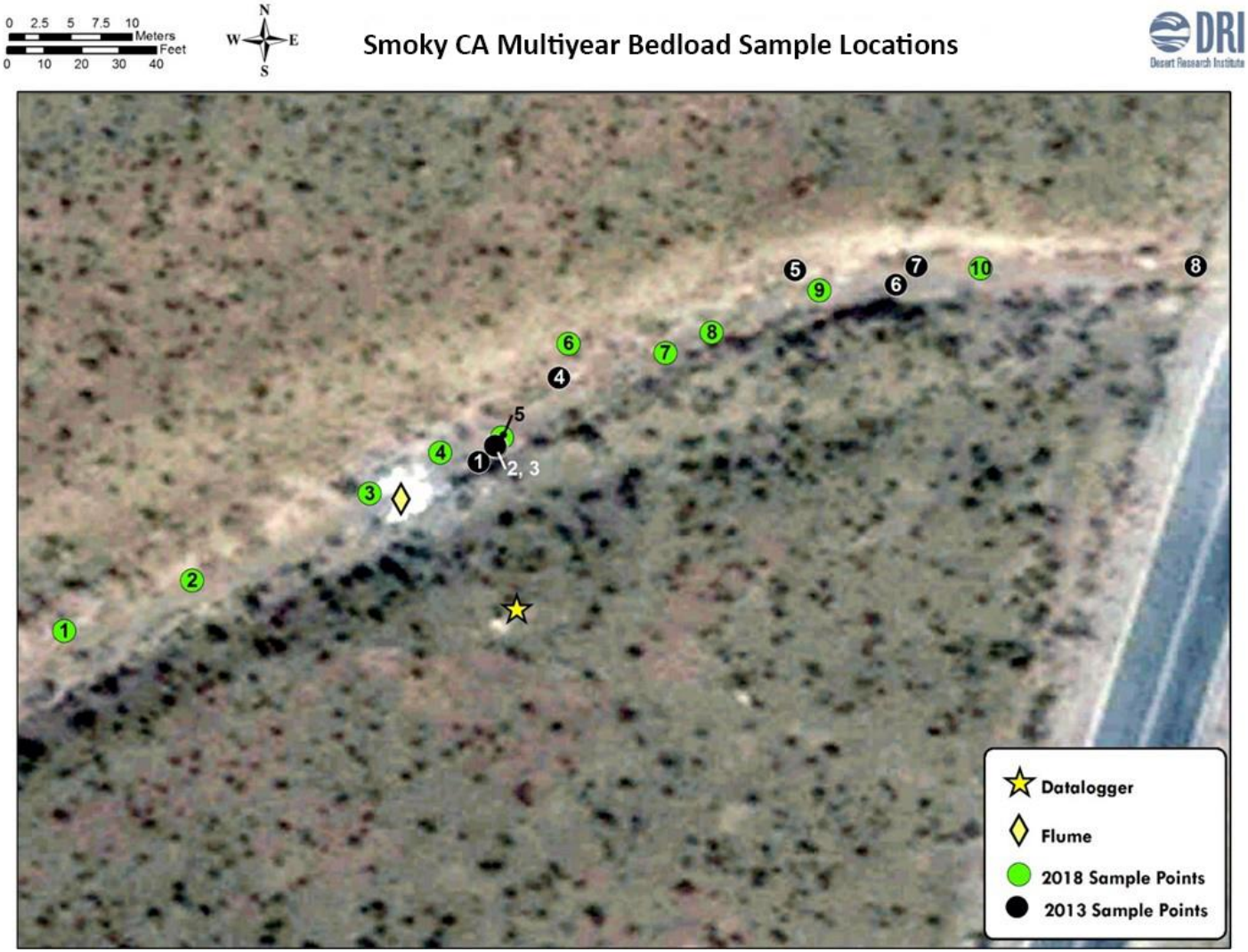

Figure E-1. Locations and IDs of samples collected on August 15, 2013 (shown in black), and August 7, 2018 (shown in green), within the Smoky CA. No spatial information is available for samples collected on August 20, 2014.

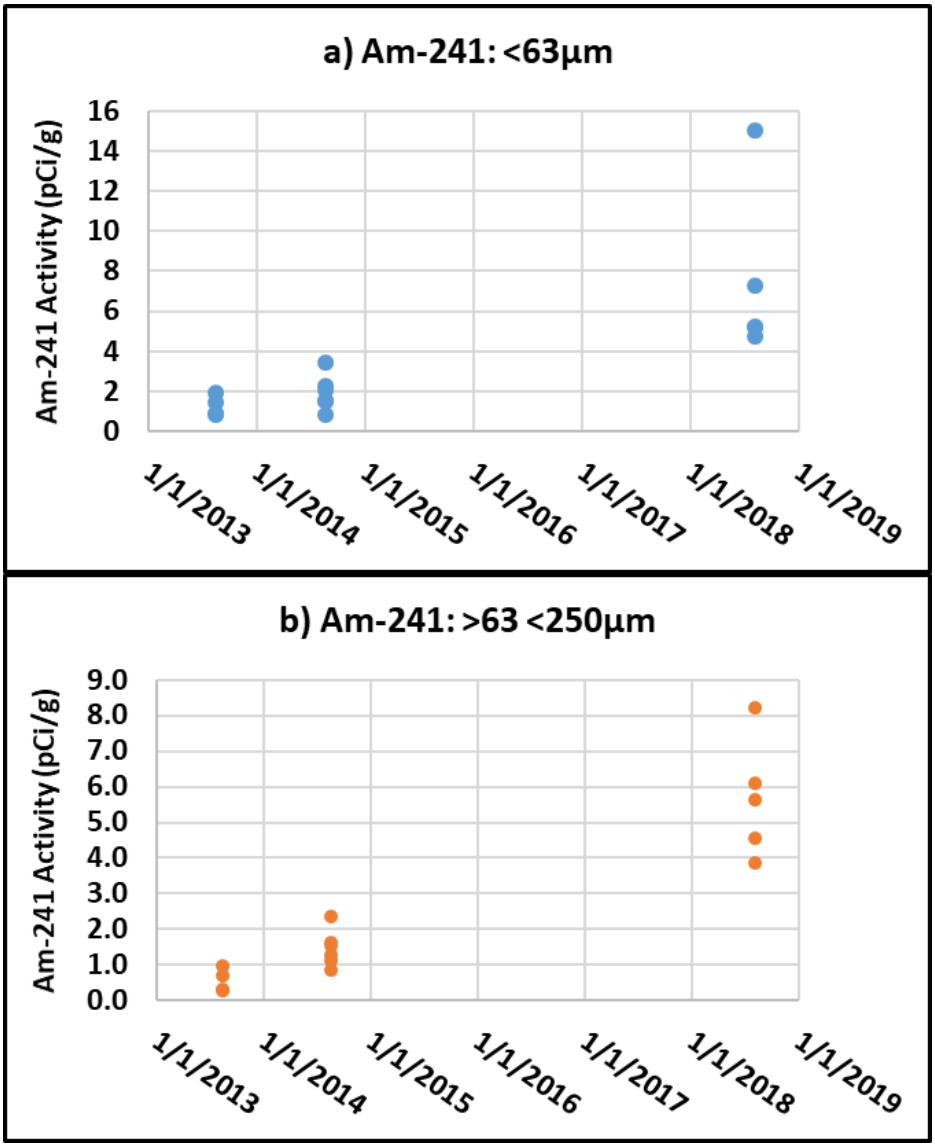

Figure E-2. ^{241}Am specific activity versus time of samples that were collected generally within the hydraulically "active" portion of the channel, where a) is the fraction less than 63 µm and b) is the fraction greater than 63 µm but less than 250 µm. Sampling activities took place on August 15, 2013; August 20, 2014; and August 7, 2018.

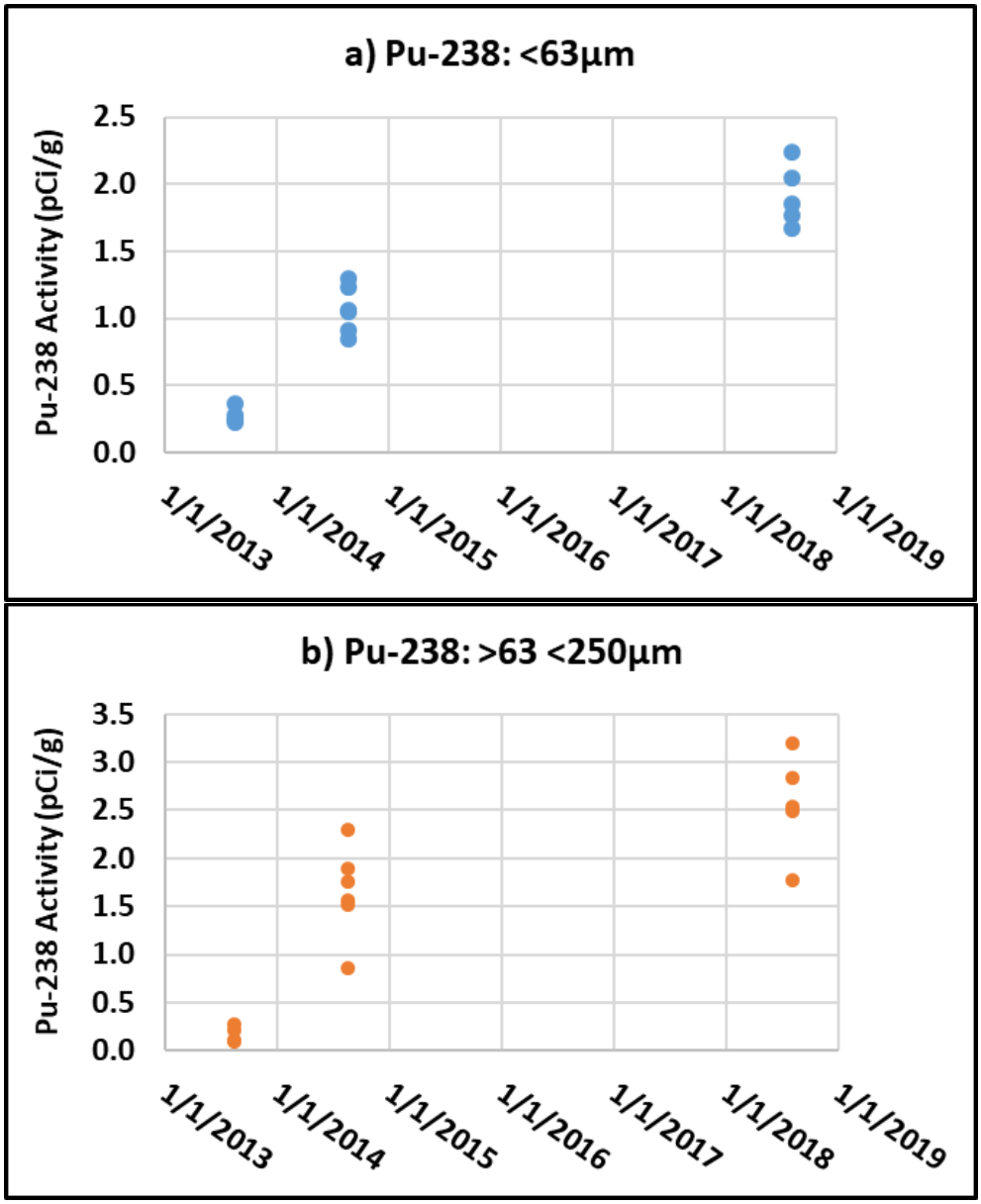

Figure E-3. ^{238}Pu specific activity versus time of samples that were collected generally within the hydraulically "active" portion of the channel, where a) is the fraction less than 63 µm and b) is the fraction greater than 63 µm but less than 250 µm. Sampling activities took place on August 15, 2013; August 20, 2014; and August 7, 2018.

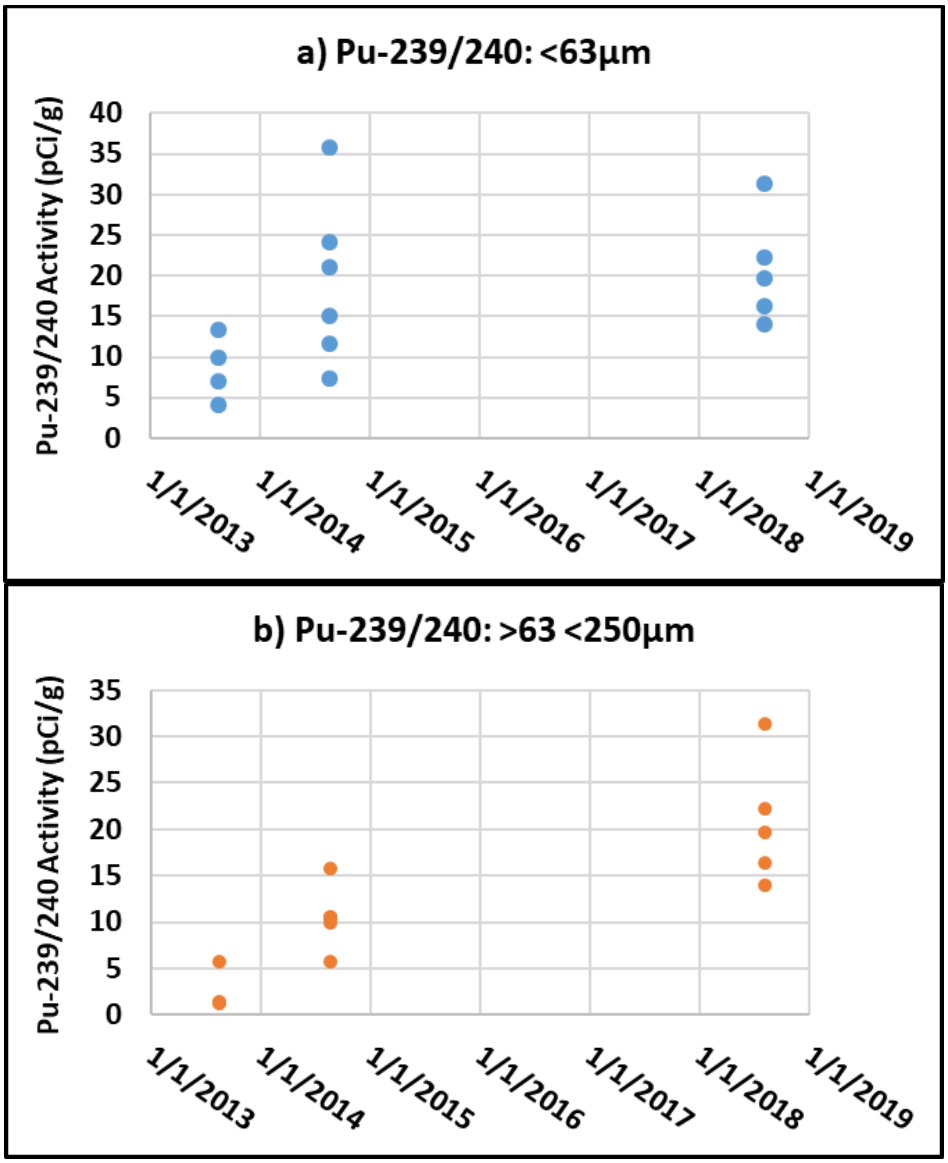

Figure E-4. $^{239+240}$Pu specific activity versus time of samples that were collected generally within the hydraulically "active" portion of the channel, where a) is the fraction less than 63 µm and b) is the fraction greater than 63 µm but less than 250 µm. Sampling activities took place on August 15, 2013; August 20, 2014; and August 7, 2018.

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