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Dust Control Planning

For the Hanford Central Plateau

September 2019

Catherine MR Yonkofski
Delphine Appriou
Janelle L Downs

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

At the Hanford Site, dust control is required during many activities for health and safety purposes and to prevent contaminant dispersal via atmospheric transport. Water is commonly used to reduce dust dispersal, but can mobilize contaminants and facilitate transport through the vadose zone to groundwater as observed with past activities within the River Corridor. To prevent contaminant mobilization associated with remediation activities in the Central Plateau, alternative approaches for dust suppression are presented considering site-specific requirements at Hanford.

There are two high-level categories of approaches to dust control: **proactive work strategies** to minimize fugitive dust generation and **reactive engineered controls** to mitigate dust generation and/or capture fugitive dust. Because a variety of activities have the potential to generate fugitive dust at a given site, there is no unique response to dust prevention and control.

In fiscal year 2018, an evaluation was completed to identify alternatives, determine limits on surface water additions, and develop information suitable for consideration in feasibility studies (Yonkofski et al. 2018). The technical basis detailed in the 2018 evaluation has been condensed into this document that provides a practical Dust Control Plan template and site-specific guidance in the appendices. This Dust Control Plan template specifically provides a workflow to 1) identify key project information, 2) identify fugitive dust sources, 3) assign dust control methods, and 4) determine appropriate monitoring practices to mitigate impacts to groundwater.

Acknowledgments

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Contents

Introduction

Water application has been the predominant dust control method at the Hanford Site due to its effectiveness, accessibility, and low cost. Use of water at or near waste sites may nonetheless lead to unintended mobilization of contaminants in the deep vadose zone to groundwater, thereby requiring additional mitigation efforts. To avoid unintended consequences of dust suppression water on contaminant transport, a practical site-specific guide on selecting and implementing dust control measures for the Hanford Central Plateau is needed.

At the Hanford Site, dust control is required during many activities for health and safety purposes and to prevent contaminant dispersal via atmospheric transport. Adverse impacts on the groundwater resulting from dust control activities have been observed. For instance, during and after excavation of the 100-C-7 waste site in the River Corridor, a spike in groundwater hexavalent chromium concentrations down gradient of the site was observed (U.S. DOE 2017). This large excavation removed soils from the surface down to the water table resulting in dust suppression water transporting hexavalent chromium to groundwater. A similar increase in groundwater uranium concentration was potentially attributable to initial remediation activities for the 316-4 burial ground (PRC-PRO-SMP-53095), which also has a relatively thin vadose zone.

Because Hanford remediation work is transitioning from the River Corridor to the Central Plateau where there is a significant inventory of contaminants in the vadose zone, dust suppression approaches will need to consider potential negative effects of water addition when the vadose zone is much thicker than the River Corridor. Planning for potential dust suppression impacts to groundwater has been applied for some remediation activities (e.g., ECF-300FF5-17-0019, Rev. 00), demonstrating the importance of quantifying the relationship between added water and potential groundwater impacts.

Currently, control measures are not widely implemented for water applied for dust suppression during surface remediation activities in the Central Plateau. Recent work by Zhang (2017) and Yonkofski et al. (2018) placed limits on dust suppression water to prevent contaminant mobilization even in the presence of a thick vadose zone. Recommended application thresholds were based on 2 mm/day or the equivalent volume of water over a 5-year period. For instance, 2 mm/day for 5 years is equivalent to ~83 truckloads (1 truckload ≅ 4,000 gallons) of water total within an area of 345 m^2. This area is provided as an example based on modeling case studies, but may easily be scaled to other size areas so long as the rate is kept contant. For this example, this is the maximum volume of water recommended without adversely accelerating contaminant transport in the vadose zone. This translates to a water application limit of 1 truckload per day over 83 days, or ~4-months (weekends excluded).

Because the use of water for dust suppression is a standard practice for surface remediation, an evaluation was completed to identify alternatives and develop information suitable for consideration in feasibility studies (Yonkofski et al. 2018). The detailed information from that evaluation has been condensed here into a practicable Dust Control Plan template with accompanying guidance in Appendices. The purpose of this template is to facilitate the process of preparing a Dust Control Plan if one is needed for operable unit activites in the Central Plateau. The template includes sections that describe relavant information that needs to be considered in preparing a Dust Control Plan. While dust control plan templates are common and used in many different situations likely to generate dust, this template for use at the Hanford Site Central Plateau has a strong focus on identifying appropriate strategies that will minimize, mitigate and control fugitive dust generated by remediation operations and with consideration of the need to protect the groundwater.

This Dust Control Plan template provides a workflow with supporting information attached in appendices. The section titles of the template and their supporting appendicies are given below:

1. Identify project contacts
2. Identify site/project information
    - Appendix B – Why Site / Environmental Considerations are Critical When Developing a *Dust Control Plan*
3. Identify fugitive dust sources
    - Appendix C – Category of Dust-Generating Activity
4. Define dust control methods
    - Appendix D – Defining the Appropriate Dust Control Strategy
    - Appendix E – Dust Suppressants
    - Appendix F – Best Management Practices for Dust Control by Activities
5. Determine appropriate monitoring practices
    - Appendix G – Dust Control Monitoring Strategies

Note: Appendix A provides a glossary of terms used within this document.

Some fields of the template come with self-explanatory guidance. Others may require additional knowledge or research to find relevant data and/or information specific to the conditions of the site or the activities. In such cases, the symbol indicates a tip box in which additional guidance or resources are provided. For other sections, including the determination of the appropriate dust control or monitoring strategy, detailed technical information are provided in Appendices accessible by clicking on the links in the template.

Dust Control Plan Template

1.0 Project Contacts

Provide name(s) and contact information of the person(s) responsible for making sure the plan is implemented, and who can be contacted in the event of a dust complaint.

1.1 Primary project contact

Name: ______________________ **Title:** ______________________

Organization: ______________________ **Address:** ______________________

Phone #: ______________________ **Email address:** ______________________

Description of contact's duties and responsibilities:

1.2 Dust control coordinator *(if any)*

Name: ______________________ **Title:** ______________________

Organization: ______________________ **Address:** ______________________

Phone #: ______________________ **Email address:** ______________________

Description of contact's duties and responsibilities:

1.3 Other contact *(if any)*

Name: ______________________ **Title:** ______________________

Organization: ______________________ **Address:** ______________________

Phone #: **Email address:** ______________________

Description of contact's duties and responsibilities:

2.0 Site/Project Information

2.1 Project identification

Provide the best available information for the site/project's geographic location, such as address, nearest major cross streets north/south/east/west.

Location: ____________________ **State:** ____________________

City: ____________________ **Other identifying features:** ____________________

Additional information (if needed):

2.2 Brief project description

Describe briefly the activities that will be taking place on the site.

2.3 Site history

Describe previous site use, past activities performed at the site, nature and extent of contamination (if any). If applicable, contamination status of the site–including distribution of contaminants across the site and levels of contaminants–may also be provided.

2.4 Site Conditions

Physical description

Provide a physical description of the site (e.g., topographic description, existing features, buildings, roads).

Climate and meteorological information

Provide any information related to the climate and/or meteorological conditions that may be influential at the location of the project (e.g., climate classification, wind and precipitation frequency).

TIP 1: Hanford Site information can be found at:

- Hanford Meteorological Station (HMS) historical climatological data available at https://www.hanford.gov/page.cfm/MetandClimateDataSummary, providing climatological data including wind, precipitation, and temperatures records.

Soil conditions

Describe the soil properties at the project location. A soil map may be optionally included.

TIP 2: Hanford Site information can be found at/in:

- PHOENIX application, available at: https://www.hanford.gov/page.cfm/PHOENIX
- CP-60925, 2018, *Model Package Report: Central Plateau Vadose Zone Geoframework*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0065500H
- ECF-HANFORD-13-0029, Rev. 5, *Development of the Hanford South Geologic Framework Model*, Hanford Site, Washington. Available at: https://pdw.hanford.gov/document/0064943H

More generally, web soil surveys from the U.S. Department of Agriculture are available at https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

Soil properties of a site may have a considerable impact on the amount of dust generated. More generally, an assessment of soil particle size distribution can help in determining the potential for particles to become airborne, and a soil profile may also provide information on the different soil layers and their potential for particle lift off.

Sensitive receptors

List any sensitive receptors that could be affected by dust emissions and their respective location in the area of the project.

TIP 3: Why focus on site/environmental considerations?

The nature of site activities, site conditions, the soil/dust itself, and nearby features are key considerations to help guide selection of the appropriate dust control measure and should therefore be characterized when developing a dust control strategy.

These key considerations are summarized in Appendix B.

2.5 Project/site plan map

Include a map that identifies the following elements: boundaries of the project, areas to be disturbed, existing roads and nearest main roads, north arrow, scale, any information to help enable the proper evaluation of dust generating sources (i.e., excavation, unpaved roads, stockpiles, loading/off-loading areas), traffic routes, prevailing wind direction (if known), and distribution of contaminants at the site (if any – see Section 2.3). Aerial photos may be provided.

Placeholder for map/project drawing

3.0 Fugitive Dust Sources

3.1 Disturbed surface area / Size of the project

Report the total area of land surface to be disturbed by including all areas of soil that may be changed from prior conditions during project operations (e.g., unpaved staging/parking areas, stockpile areas, excavation, hauling). Similarly, the total areas left inactive for several days are reported here. This can include but is not limited to open areas, or stockpiles.

Total area of project site (e.g., acres, m^2): ______________________

Total surface area to be disturbed (e.g., acres, m^2): ______________________

Any disturbed areas left inactive for more than 7 days[1] (e.g., acres, m^2): ______________________

Estimated amount of import/export material to/from the project site *(if required by regulatory authority)* ______________________

3.2 Dust-generating activities dates

Report expected start and completion dates of dust-generating activities and soil disturbances/remediation activities to be performed. If operations are not phased, indicate "N/A" for Phase A-D entries.

Expected start date:		**Completion date:**	
Phase A start:		**Completion A:**	
Phase B start:		**Completion B:**	
Phase C start:		**Completion C:**	
Phase D start:		**Completion D:**	

3.3 Identification of sources of fugitive dust emissions

The identification of all sources of fugitive dust emissions is critical for identifying the optimal dust control measures for the operations performed on the site. Each category that applies to the actions expected on the site and likely to generate dust must be identified by checking the appropriate box(es).

The sources of potential fugitive emissions are divided into six main categories. For more details about these categories, please refer to Appendix C.

Does the project include vehicle / motorized equipment? ☐ Yes ☐ No

*If **"yes"**, provide information in Section 4.0– **Category A: Vehicle/ Motorized Equipment***

[1] The number of days may vary depending on the guidance and/or requirements of the regulatory authority.

Does the project include disturbed or cleared areas? *If **"yes"**, provide information in Section 4.0 – **Category B: Disturbed/Cleared Surface Area***	☐ Yes ☐ No
Does the project include bulk material handling? *If "**yes"**, provide information in Section 4.0 **– Category C: Bulk Material Handling***	☐ Yes ☐ No
Does the project include any demolition activities? *If **"yes"**, provide information in Section 4.0 **– Category D: Demolition***	☐ Yes ☐ No
Does the project include general construction, landscaping, and/or maintenance activities? *If **"yes"**, provide information in Section 4.0 – **Category E: Landscaping / Maintenance Activities***	☐ Yes ☐ No
Does the project include any other dust-generating activities not covered by the questions above?? *If **"yes"**, provide information in Section 4.0 – **Category F: Others***	☐ Yes ☐ No

4.0 Definition of Dust Control Measures

4.1 Assign dust control

Use the table below to list mitigation methods that will be implemented to control dust emissions for any fugitive dust sources identified in Section 3.3. Applicable dust control methods are categorized as ***work strategies*** *to mitigate the amount of dust generated, and* ***engineered controls****, which are enacted in response to fugitive dust.*

*For each category of dust-generating activity identified in Section 3, dust control methods should be identified as primary (**P**) control measures or contingency (**C**) control measures. Contingency methods may become necessary in the event that the primary dust control strategy is not adequate or effective.*

In this table, two columns are shaded in blue and refer to engineered controls requesting the use of water, water with surfactants, or water mixed with palliatives. Water applications should be managed and controlled cautiously to prevent unintended mobilization of contaminants from the vadose zone to groundwater. Should water, water with surfactants, or water mixed with palliatives be used as primary or contingency methods to control dust emissions, further information related to the application rate and frequency is needed in Section 4.2.

Note: Dust control measures listed in the table do not represent an exhaustive list of options available; therefore, alternative technologies that are technically feasible under the site-specific conditions may also be considered. Non-listed control measures may be added by editing the table in the row(s) for "Others". An alternative plan may require additional planning, permitting, or other regulatory compliance requirements to implement.

TIP 4: How to determine the best strategy regarding dust control

Selection and implementation of an appropriate dust control strategy depends on several factors, including the nature of the activity generating dust, feasibility of use, frequency of application necessary to achieve desired level of control, cost of application, and whether the goal is interim suppression of uncontaminated dust, suppression of contaminated dusts, or final restoration of remediated areas. In addition, an evaluation of dust suppression technologies must consider whether dust suppression agents, if used, will break down to become hazardous or interact with site-specific conditions to present a future chemical/radiological hazard.

- General information about both work strategies and engineered controls that can be implemented is presented in Appendix D.
- Decription of the main categories of Dust Suppressant is provided in Appendix E.
- Suggestion of Best Practices are presented in Appendix F.

SOURCES OF FUGITIVE DUST EMISSIONS			**WORK STRATEGIES**										**ENGINEERED CONTROLS**														
																			Palliative								
			Minimize disturbed or cleared area / phase work	Minimize drop height	Limit/reduce vehicle speed	Limit stockpile height/slope	Restrict vehicle access	Train site personnel	Limit vehicle capacity / Cover haul trucks	Cease operations	Street sweeper	Others	Windbreaks / Wind barriers	Enclosure systems	Surface roughing	Surface upgrade / Mechanical stabilization	Install trackout control device	Vegetation groundcover / revegetation	Water application[1]	Surfactants / Water[1]	Hygroscopic salts	Polymers	Organic non-petroleum products	Electrochemical additives	Clay additives	Others	
*For each category of dust-generating activity identified in Section 3.3, check all categories or sub-categories that apply and indicate the chosen control measure(s): **"P"** for primary control measure; **"C"** for contingency control measure*																											
A – Vehicle/ Motorized Equipment																											
A.1	Unpaved staging areas or parking areas	☐																									
A.2	Unpaved roads / Haul roads	☐																									
A.3	Paved roadways	☐																									
A.4	Others: ________________	☐																									
B – Disturbed/Cleared Surface Area																											
B.1	Before active operations	☐																									
B.2	During active operations	☐																									
B.3	Inactive period (temporary stabilization)	☐																									
B.4	Permanent stabilization of disturbed surface	☐																									
B.5	Others:________________	☐																									
C – Bulk Material Handling / Earthmoving																											
C.1	Hauling / Transporting	☐																									
C.2	Bulk material stacking, loading, and unloading operations	☐																									
C.3	Active stockpile	☐																									
C.4	Inactive stockpile	☐																									
C.5	Active excavation site	☐																									

[1] The two columns shaded in blue refer to engineered controls requesting the use of water, water with surfactants, or water mixed with palliatives. If water, water with surfactants, or water mixed with palliatives are planned to be used as primary or contingency methods to control dust emissions, further information related to the application rate and frequency is needed in Section 4.2.

For each category of dust-generating activity identified in Section 3.3, check all categories or sub-categories that apply and indicate the chosen control measure(s): ***"P"*** *for primary control measure;* ***"C"*** *for contingency control measure*																											
C.6	Inactive exaction site	☐																									
C.7	Others:________________	☐																									
D - Demolition Activities		☐																									
E – General Construction / Landscaping / Maintenance Activities		☐																									
F - Others: ___________________________		☐																									

4.2 Water and other fluid application (rate and frequency)

Complete this section if water, water with surfactants, or water mixed with palliatives will be used as control methods for limiting fugitive dust emissions and stabilizing surface areas.

Water and other fluid application limits

Maximum fluid application rate: **2 mm/day**[*]

TIP 5: Determination of maximum total fluid application rate limit

Within the Central Plateau of the Hanford Site, the maximum fluid application rate is recommended not to exceed 2 mm/day (Yonkofski et al. 2018).

Maximum daily volume: ____________

TIP 6: Calculation of the maximum daily volume limit

Maximum daily volume = Maximum ***total fluid application rate*** *× total application area*

Example: 2 mm/day × 345 m^2 = 690 L ≅182 gallons

Maximum total volume: ____________

TIP 7: Calculation of the maximum volume limit

Maximum total volume = Maximum ***daily fluid application rate*** *× total application area × 5 years*

Example: 2 mm/day × 345 m^2 × 5 years = 83 truckloads[§]

Note: The 2-mm/day application limit was calculated from a 5-year application duration.

If dust palliatives are used, provide product and application information in the following table. Additionally, any information that fully describes the product use (if different than water) may also be attached to the dust control plan for tracking purposes. This includes but is not limited to information such as products specifications (e.g., product safety data sheets), label instructions, environmental impacts, and approvals or certifications related to the appropriate and safe use for ground application.

[*] Maximum application rate for the Central Plateau. See Yonkofski et al. 2018.
[§] One truckload ≅ 4,000 gallons.

	PALLIATIVE (e.g., water, water surfactants)	MANUFACTURER NAME	APPLICATION FREQUENCY	APPLICATION EQUIPMENT (e.g., spray boom)
A – Vehicle/ Motorized Equipment				
B – Disturbed/Cleared Surface Area				
C – Bulk Material Handling / Earthmoving				
D - Demolition Activities				
E - Landscaping / Maintenance Activities				
F - Others:				

Water supply (if water is used as a control method)

Identify water supply(ies) by checking the appropriate box(es). Location of each supply can be identified on the facility plan (Section 2.5).

☐ Storage tanks <add ID / coordinates>

☐ Wells <add ID / coordinates>

☐ River / Canal / Pond / Lake <name / withdrawal location>

☐ Other <description>

5.0 Monitoring

5.1 Identify strategies to minimize water infiltration and monitor fugitive dust

List the methods that will be implemented to monitor and control water application at the project site in the following table. Identify any methods to be used and/or monitoring equipment that will be deployed to assure air quality is maintained at acceptable levels during project execution.

Note: Monitoring and water control methods in the table do not represent an exhaustive list of options available; therefore, alternative approaches may also be considered. Non-listed methods may be added by editing the table in the row "Others".

TIP 8: How to determine the best strategy regarding control and monitoring of water application?

Selection and implementation of an appropriate water application control and monitoring strategy depends on several factors including the existence, distribution, and nature of underlying contaminants, and project resources. In general, it is always recommended to begin by planning work strategies which limit dust generation. Water, or fluid, monitoring logs should **always** be kept and regularly reviewed to ensure the application amount remains below thresholds. In scenarios with multi-pronged approaches to remediation, where the total amount of fluid applied to the surface is unknown or changes to the subsurface contaminant distribution are ongoing, more sophisticated geophysical methods may be of use.

- Detailed information about potential monitoring strategies are presented in 6.0Appendix G.
- Suggested Best Practices are presented in Appendix F.

DUST-GENERATING ACTIVITIES		**WATER APPLICATION CONTROL**					**NEAR-SURFACE SOIL WATER AND INFILTRATION**							**GROUNDWATER/ PERCHED WATER TABLE CHANGES**			**AIR**				
		Water Application Logs	Vehicle Speed and Boom Pressure Records	Water Truck Metering System	Variable Rate Application System	Survey for Standing Water	Electrical Resistance/Heat Dissipation Blocks	Time-Domain Reflectometry	Tensiometers	Neutron Probe Measurements	Borehole Ground Penetrating Radar	Passive Capillary Lysimeters	Electrical Resistance Tomography (ERT)	Monitor Water Elevations in Nearby Downgradient Wells	Monitor Dry Wells for Water	ERT Detection of Perched Water	Visual Survey	EPA Method 9 Opacity	Particulate Matter Monitoring Instrumentation*	Meteorological Station/Anemometer and Vane for Wind Speed and Direction	Other
Check all categories of dust-generating activities identified in Section 3.3 and indicate the chosen monitoring or control method(s): “P” for primary method; “C” for contingency method																					
A – Vehicle/ Motorized Equipment	☐																				
B – Disturbed/Cleared Surface Area	☐																				
C – Bulk Material Handling / Earthmoving	☐																				
D - Demolition Activities	☐																				
E – General Construction / Landscaping / Maintenance Activities	☐																				
F - Others: ____________________	☐																				

** Specify instrumentation methods for PM 10 and PM 2.5 as required.*

6.0 References and Bibliography

The following documents were used to develop the *Dust Control Plan template* and can provide additional guidance on the implementation of a dust control strategy.

Department of Environment and Conservation. 2011. *A guideline for managing the impacts of dust and associated contaminants from land development sites, contaminated sites remediation and other related activities*. Government of Western Australia, 2010529.

CP-60925, 2018, Model Package Report: Central Plateau Vadose Zone Geoframework, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0065500H

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Natural Resources Conservation Service. 2019. *Dust Control on Unpaved Roads and Surfaces.* Conservation Practice Standard CODE 373, Washington, D.C., 373-CPS-1.

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U.S. DOE. 2017. *Hanford Site Groundwater Monitoring Report for 2016,* DOE/RL-2016-67, Revision 0, CH2MHill, U.S. Department of Energy, Richland, Washington

U.S. EPA. 1985. *Handbook Dust Control at Hazardous Waste Site*. EPA/540/2-85/003. U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, Cincinnati, OH.

Yonkofski C, D Appriou, X Song, JL Downs, CD Johnson, and VC Milbrath. 2018. *Water Application for Dust Control in the Central Plateau: Impacts, Alternatives, and Work Strategies*. PNNL-28061. Pacific Northwest National Laboratory, Richland, WA.

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Appendix A – Glossary

Active operations: Any anthropogenic activity that is capable of generating (including but not limited to) bulk material storage, handling or processing; earth moving; soil or surface disturbance (e.g., trenching, blading, scraping, clearing, grubbing, topsoil removal); construction, renovation, or demolition activities; movement of motorized vehicles on any paved or unpaved roadway or surface, lot or parking area; or the tracking out or transport of bulk material onto any paved or unpaved roadway.

Anthropogenic: Caused, created, or produced by people or human activity.

Bulk materials: Sand, gravel, soil, aggregate, or any other inorganic or organic solid material capable of creating fugitive dust.

Disturbed surface area or surface disturbance: Natural or manmade portion of the earth's surface (or material placed thereupon) that has been physically moved, uncovered, destabilized, or otherwise modified from its undisturbed native condition, thereby increasing the potential for the emission of fugitive dust.

Earthmoving: Use of any equipment for an activity that may generate fugitive dust emissions, including but not limited to grading, cutting, filling, leveling, excavating, trenching, loading or unloading of dirt or bulk material; demolishing, blasting, drilling, adding to or removing of material from open storage piles; backfilling; or soil mulching.

Excavation: Any digging, trenching, quarrying, or extraction.

Fugitive dust or dust: Organic or inorganic particulate matter. Water vapor, steam, or particulate matter emissions emanating from a duct or stack of process equipment are not fugitive dust.

Inactive disturbed surface area: Any disturbed surface area upon which active operations have not occurred or are not expected to occur for a period of several consecutive days.

Open storage pile: Accumulation of bulk material that is not fully enclosed, covered, or chemically stabilized.

Paved roadways: Asphalt, recycled asphalt, concrete or asphaltic concrete, routinely maintained asphalt millings, or combinations thereof, that cover a surface traveled or used by motor vehicles.

Source or source of fugitive emissions: Origin of fugitive dust emissions.

Stockpile: Depositing of bulk material by mechanical means for the purpose of creating a pile formation on top of an existing natural or manmade surface.

Track-out or tracking: Bulk material deposited by a motor vehicle or vehicles on an unpaved or paved publicly or privately owned roadway if the bulk material can become airborne due to mechanical or wind action.

Unpaved roadway: Unpaved route traveled by a motorized vehicle.

Appendix B – Why Site / Environmental Considerations are Critical When Developing a *Dust Control Plan*

Site and environmental conditions are key considerations that will help guide the selection of appropriate dust control measures, and are summarized in the table below. These factors are all influencing levels of dust and should therefore be characterized in the *Dust Control Plan*.

Table B.1. Considerations Influencing Levels of Dust and Selection of a Dust Control Strategy

Consideration	Why?	Description
Nature of the activity/work	The work to be conducted will affect the dust levels. Some activities may generate more dust than others.	• Type of work • Size of disturbed area • Duration and time of year of the dust-generating activity • Continuity of work/activity (e.g., continuous or intermittent) • Size and degree of activity in traffic areas / non-traffic areas • Evaluation of need for permanent dust control
Site characteristics	Physical characteristics of the site may have a significant influence on the amount of dust generated.	• Protection from wind provided by topography, surface features (e.g., structures), and/or undisturbed vegetation • Weather and climate conditions (time-of-year dependent): – Prevailing wind direction and speed – Temperature – Precipitation/evaporation conditions • Concentrations and distributions of contaminants on the site • Potential for chemical interaction (leaching)
Site history / Contamination level	Pre-existing conditions related to past activities may determine the risk potential for dust of the site and may prevent the use of some dust control methods (e.g., water to avoid contaminant remobilization).	• Concentrations and distributions of contaminants on the site • Potential for chemical interaction (leaching)
Soil characteristics	Soil properties will have a considerable impact on the amount of dust generated.	• Soil type (particle size distribution) • Soil moisture
Proximity to sensitive receptors, other waste sites, or other land uses	The proximity of a site to sensitive receptors has an influence.	• Distance/proximity to waterways, facilities, vegetation • Distance to other land uses and nature of topography between site and other land uses • Effect of dominant wind direction on other land uses
Side effects of dust control method / Water requirements	All dust control measures are not appropriate for a given activity or site. Adverse environmental effects should be considered.	• Knowledge of potential adverse effects of dust control methods • Depth/location of water table and saturated/oversaturated areas

Appendix C – Category of Dust-Generating Activity

- **Category A: Vehicle/ Motorized Equipment**

  This category refers to fugitive dust emissions generated by motorized equipment and miscellaneous vehicle traffic. This includes traffic on unpaved staging areas, unpaved parking areas, unpaved material storage areas, unpaved access areas, and haul roads and paved roadways.

- **Category B: Disturbed/Cleared Surface Area**

  This category refers to fugitive dust emissions from soil being disturbed or land surface being exposed. This can include earth moving or site-clearing activity.

- **Category C: Bulk Material Handling/Storage**

  This category refers to fugitive dust emissions generated by stacking, loading and unloading operations, trenching, backfilling, and importing or exporting bulk materials from one area to another. This category also includes airborne dust emitted from active and inactive storage piles.

- **Category D: Demolition**

  This category refers to fugitive dust emissions generated during demolition operations.

- **Category E: General Construction / Landscaping / Maintenance Activities**

  This category includes variety of general construction, maintenance, and site operation activities that have the potential to generate dust. The types of dust-generating activities in this category include facility construction and ground surface grading/vegetation removal to form workspaces or buffer areas (e.g., for well pads, laydown yards, construction sites, fire protection buffers). Such activities result in a disturbed ground surface and may themselves generate dust or result in windborne dust emissions from the cleared and exposed ground surfaces.

- **Category F: Others**

  Any additional or other category not listed and likely to generate dust emissions must be identified in Category F.

Example 1: Does the project include vehicle / motorized equipment?

If the answer is yes, further information is requested in **Section 4** to define the appropriate strategy to prevent and/or control dust emissions resulting from vehicle traffic.

Appendix D – Defining the Appropriate Dust Control Strategy

There are two high-level categories of approaches to dust control: **proactive work strategies** to minimize fugitive dust generation and **reactive engineered controls** to mitigate dust generation and/or capture fugitive dust. Because a variety of activities have the potential to generate fugitive dust at a given site, there is no unique response to dust prevention and control. Dust generation and transport may be prevented through appropriate strategies, good construction and maintenance practices, and engineered controls. Work strategies that prevent dust generation include best management practices for construction/excavation activities, and scheduling work to minimize activities when weather or climate conditions are conducive to dust generation. Engineered control measures may be used to help stabilize soil surfaces, reduce wind speed at ground level, or otherwise minimize dust generation.

Table D.1 provides a compilation of the main prevention and control measures that may be implemented. Measures are categorized as “work strategies” or “engineered controls.” Dust palliatives are described with additional details in Appendix E .

Table D.1. Dust Control Methods

Method	Description
Work Strategy	
Project Timing / Work Staging	Schedule work to be conducted during a time of the year that will reduce the potential for dust generation. Activities with high dust-causing potential should not be carried out during adverse wind conditions.
Minimize Disturbed/Cleared Area	Limit the size of the area where soil is disturbed or land surface is cleared/exposed. The exposed area can be limited by working in phases and clearing just the necessary area while maintaining surrounding vegetation on inactive areas (which helps dissipate wind velocity at the ground surface).
Limit/Reduce Vehicle Speed	Reduce vehicle speeds to help prevent entrainment of dust from the tires and vehicle-generated wind.
Transport	Keep the truck load below the freeboard to minimize spillage and wind exposure. Consider impact of truck load/weight on road surface integrity. Provide covers for haul trucks transporting bulk materials to prevent wind-blown dust during transport.
Minimize Drop Height	Minimize the drop height from loaders and excavators to reduce dust emissions. Gentler transfer of soil will result in less dust.
Restrict Site Vehicle Access	Restrict vehicle access to the site to essential vehicles only.
High Wind Restriction	Restrict earthmoving or other soil-disturbance activities when local wind speeds exceed a certain value.
Maintenance and Training	Implement routine maintenance procedures such as: • Staff awareness of the potential for dust generation • Maintenance of work controls (e.g., tarping, grading) Wash vehicles to prevent the spread of contamination
Limit Stockpile Height / Slope	Limit the height and slope of stockpiles to minimize wind exposure and surface area.
Cease Operations	Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues.

Method	Description
Engineered Control	
Wind Barriers / Windbreaks	Develop and emplace windbreaks in upwind positions to slow wind speed or ‘break’ the wind. Windbreaks can be developed with man-made materials or vegetation, depending on the configuration of the site. Set up wind barriers to control dust emissions over short distances.
Enclosure	Either fully enclose the site or use a three-sided structure as a shelter from predominant winds. Unroofed three-sided structures would typically be used for stockpiles.
Surface Roughening	Stabilize an exposed area during periods of inactivity or when vegetation cannot be immediately established by tilling or disking the surface of disturbed soils to produce a rough surface or ridges.
Surface Upgrade/Mechanical Stabilization	Increase surface strength by improving particle size distribution, shape, and/or mineral types, followed by compaction. Where a soil has few fines, clay additives can improve mechanical stabilization. Technology is typically for unpaved roads.
Mulch/Ground Cover	Use natural or synthetic mulch/cover materials such as gravel/rocks, wood chips/bark, rubber, and other materials as a barrier to wind entrainment and moisture loss. Applicable to inactive areas.
Removable Ground Cover	Use anchored plastic/textile sheeting to cover open surfaces during windy periods and periods of project inactivity, or for areas not actively being worked.
Vegetation/Revegetation	Vegetation acts in several ways to achieve effective dust control. Plant roots act to mechanically stabilize and retain soil, while the aboveground plant bodies reduce wind speed at the ground surface. Revegetation is applicable for areas inactive for 30 days or more (to allow time for growth). This dust control method requires application of water to maintain plant health.
Wet Suppression	Use regular application of water (possibly with surfactants) to keep soil moist such that fine particles agglomerate and are too dense to become airborne fugitive dust. This control method is also used to capture fugitive dust that is generated by site activities.
Chemical Stabilization	Apply chemical dust suppressants to alter soil properties (particle size, agglomeration, density), mechanical strength, and/or wind exposure (e.g., with a coating/crust) to prevent dust generation. Chemical suppressants are less often used for dust capture. They provide generally immediate coverage and protection and are effective in areas with limited disturbance or traffic. They also provide a longer-term solution compared to watering, although it may be necessary for the ingredients to be evaluated to avoid any adverse environmental effects.

Appendix E – Dust Suppressants

Dust suppressants, also referred to as dust palliatives, abate dust by changing the physical properties of the soil surface by either agglomerating the fine particles, adhering/binding the particles together, or increasing the density of the surface material. They reduce the ability of light friction/abrasion or wind to lift and suspend the surface particles. In general, dust suppressants fall into the 10 categories described further below.

Selection of the best dust control measures, and therefore potentially dust suppressants, must include a sound understanding of both the dust-generating activities and the potential environmental impacts of their application.

> Performance and limitations of dust suppressants with their typical application rate and frequency are discussed in Yonkofski et al. 2018.

Water

The addition of water to soils and materials that need dust control continues to be one of the most common suppression techniques and is usually the most cost-effective short-term solution for dust control. Adding or spraying water prevents dust by increasing the humidity and moisture content at the surface, thereby temporarily agglomerating the particles and preventing them from being entrained, suspended, and transported. The downside of watering is that this agglomerating effect is temporary, depending on the evaporative demand and the rate at which the surface dries. Disadvantages of regular use of water may also include increased slipperiness of surfaces, formation of mud, and limitation on use when temperatures fall below freezing. Adding too much water may also cause the formation of puddles of standing water, muddy conditions, and increased infiltration of water to groundwater, increasing the potential for contaminant remobilization. Too little water will not provide adequate wetting of the material, which is critical to ensure that smaller dust particles stay adhered to larger particles and do not become airborne.

Water with Surfactants or Foaming Agents

Surfactants are non-petroleum-based organic chemicals that, when added to water, reduce surface tension and improve the water's ability to wet surfaces and form fine droplets. After water evaporates, the surfactants remain with the particulate matter and the residual surfactant can increase particle agglomeration through electrostatic attraction. Surfactants also allow for better water penetration into subsurface soil layers before and during active earthmoving.

Some dust suppressants can also be applied as foams. Foaming agents convert water and air (may require compressed air) into foam that can be sprayed or blown on surfaces. Foam provides more surface area coverage and better wetting and adhesion to dust particles. The advantages of foam over liquid sprays are improved liquid distribution, resulting in lower liquid feed rates, and improved fine particle capture, which can reduce breathable dust. The increased efficiency in liquid distribution can reduce water requirements in wet systems by as much as 50% or more. Foam sprays are among the most promising methods that minimize water use.

Water-Absorbing Products / Salts and Brines (hygroscopic salts)

Water-absorbing salts can be applied to surfaces or mixed into the surface to provide hygroscopic functionality by absorbing small quantities of water from the atmosphere, agglomerating the fines, and holding the aggregate matrix together through suction forces. The two most common water-absorbing treatments are calcium chloride and magnesium chloride. This type of treatment is typically applied to suppress dust on gravel or aggregate roads. The salts can be purchased as powders, pellets, flakes, or in water solutions. However, hygroscopic salts do not work well in excessively wet or excessively dry climates. In wet regions, the salts dissolve under heavy precipitation and leach through the soil. In semi-arid regions, such as Hanford, the low humidity during the summer months may not be sufficient for the salts to effectively absorb water.

Petroleum Products

Petroleum-based products have a long history of use for stabilizing soils and reducing dust emissions. The available treatment products are derived from petroleum refining and include diluted asphalt emulsions (created by dispersing asphalts as small droplets of water), base and mineral oils, petroleum resins, and synthetic fluids. Petroleum products are generally not water soluble or prone to evaporation and can be very effective for dust control.

Asphalt emulsions, petroleum resins, and synthetic fluids with binders have a cementing action that stabilizes the treated surface and preserves fine particles. A number of asphalt emulsions have been approved for use and are effective across a broad range of soil types and climates. These products do not lose effectiveness through typical climatic variations and are most often applied to stabilize trafficked surfaces, but their use is expensive due to the greater material costs and specialized application equipment.

Base oils and synthetic fluids without binders also provide dust control/fines preservation. Base or mineral oil does not dissolve in water and is not diluted for application. It is often mixed with a binder such as an organic non-petroleum treatment, another organic petroleum treatment, or a synthetic polymer to improve stabilization properties. Synthetic fluids are similar to base oils in terms of properties and performance, but the processing produces a more refined oil, which has less environmental impact and fewer use restrictions.

Organic Non-Petroleum Products

Organic non-petroleum products include substances such as glycerin/glyceride-based treatments; lignosulfonates; molasses or sugar-based treatments; plant oils (e.g., soy, linseed, rapeseed, canola, or palm oils); and resins such as tall oil pitch rosins. Organic non-petroleum constituents are primarily derived from plant-based industries, including the food industry and paper industry. These products act as a “glue” to bind or agglomerate fines and coarser particles, and are an effective means to control dust either as a topical application or as a mixed in treatment. They perform best under arid and semi-arid conditions. Most of the materials are water-soluble and generally require re-application to remain effective.

Polymers

Polymers, both natural and synthetic, are probably the most ubiquitous constituent of soil stabilization additives besides water. Polymers are large, long-chain molecules with a high charge density composed of small, repeating units (monomers). Polymers can be cationic, anionic, or nonionic. Anionic polymers are the most common form used in soil amendments and can promote the formation of larger floccules (loose aggregations suspended in liquid) that settle out of solution in the presence of cations. As only a small part of the anionic polymer is involved in adsorption, the remaining polymer tail can form bridges between particles. The net effect is one of strengthening soil aggregates, increasing infiltration, and decreasing runoff, thereby reducing erosion.

Synthetic polymer emulsions can be diluted in water when applied, but once they have dried, they should not re-emulsify or leach from the road. Generally, they are not effective as spray-on applications due to their forming a “skin” on the surface of the road that typically abrades relatively quickly under traffic; however, some manufacturers have introduced specific formulations that avoid this. Ultimately, the effectiveness of any particular polymer formulation is dependent upon the type of polymer, as well as the physiochemical properties of the soil upon which it is applied and the application objective.

Electrochemical and Enzyme Additives

Electrochemical and enzyme stabilizers create an electrochemical and/or enzymatic bond between fine particles that reduces the particles’ affinity for water. Although these chemicals do promote binding of fine particles, dust control over long periods is often insufficient for the treatments to be considered as dust suppressants. These stabilizers may be incorporated and then followed by a separate dust suppression treatment on the surface.

Electrochemical additives include sulfonated petroleum, ionic stabilizers, and bentonite. These products neutralize soil types that attract water and allow bonds to form between particles. Electrochemical stabilizers need to be worked into the upper layers to provide dust control and require relatively high clay contents to perform satisfactorily.

Enzymatic stabilizers contain protein molecules that decrease surface tension in water and catalyze specific chemical reactions with soil molecules to form a cementing bond and reduce the soil’s affinity for water. These products require the presence of clay and a relatively high fines content to work effectively.

Clay Additives

Clay additives are used to mechanically stabilize unpaved road materials that have low fines contents and/or too low plasticity. Bentonite is the most common clay additive—and the clays must be thoroughly mixed into the soils. Addition of clay leads to agglomeration of fine particles; however, as with electrochemical additives, the level of dust control is usually insufficient and an additional dust suppression treatment at the surface is required. Clay additives are most useful in construction and maintenance of unpaved roads and are not likely to be a satisfactory dust suppression treatment for Hanford applications.

Cementation and Aggregation Agents

Cement, concrete, and lime have a long history of use to stabilize soils and protect against wind and water erosion. A wide range of cement-based paving options are available. From a general perspective, the type of application determines the amount of cement needed. For instance, soil treated with a relatively small proportion of cement (2% to 6%) is referred to as “cement-modified soil”. Alternatively, “soil-cement” refers to a highly compacted mixture of soil, cement, and water with a higher concentration of cement. Soil cement is impervious to water, provides a high strength, and is well suited for trafficked areas.

Hydrated lime is also a common method used for soil stabilization. Although hydrated lime ($Ca(OH)_2$) may be more effective than cement to stabilize heavy clay soils, its efficiency is very limited in sandy soils.

Concrete contains the same ingredient as cement but in a different proportion. Concrete pavements are recommended whenever a durable and low maintenance option is required. There are particularly well adapted for very heavy trafficked areas.

Biological Binders

These types of dust suppressants [e.g., blue-green algae (cyanobacteria) inoculants, microbial polymers, and bacteria-mediated biomineralization] may be future alternatives to chemical stabilization of soils in semi-arid and arid climates. Organism growth and/or secretion of biological compounds act to bind soil particles together, reducing the erodibility of the surface. Inoculants of cyanobacteria that can be applied as slurries to the surface are currently under development, and field testing shows promise. Without standard testing procedures to predict their performance under field conditions, small-scale trials should be initiated and evaluated for efficacy prior to large-scale applications. Biopolymers have high specific surfaces with electrical charges, which enable direct interactions between the biopolymers and fine soil particles, thereby creating biopolymer-soil matrices that may be able to resist wind erosion.

Biomineralization refers to mineral precipitation in soil pores via biological organisms. Microbial induced calcite precipitation (MICP) is the most recognized mechanism and has been suggested as a promising method for dust suppression. MICP occurs when microorganisms convert urea to ammonium and carbonate, which allows calcium carbonate precipitates to form and subsequently bind with soil grains.

References

Yonkofski C, D Appriou, X Song, JL Downs, CD Johnson, and VC Milbrath. 2018. *Water Application for Dust Control in the Central Plateau: Impacts, Alternatives, and Work Strategies*. PNNL-28061. Pacific Northwest National Laboratory, Richland, WA.

Appendix F – Best Management Practices for Dust Control by Activities

Best management practices to effectively control fugitive dust emissions are listed below by category of dust-generating activities. Note that this does not necessarily represent an exhaustive list of methods that can be implemented. Depending on the site conditions, dust control may be driven by groundwater protection in addition to health and safety. For each category and sub-category, the methods are ranked based on their protectiveness of groundwater, from preferred primary options to more intensive water-application options. When groundwater protection may be of concern, it is recommended to design dust control strategies using a similar ranking.

A – Vehicle/ Motorized Equipment

A-1: Unpaved staging areas/ unpaved parking areas/unpaved staging area

- Implement traffic controls, including decreased speed limits, vehicle access restrictions and controls, road closures or barricades, off-road vehicle access control
- Pave using petroleum products (e.g., asphalts emulsions), asphaltic concrete, concrete
- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if water usage is thoroughly controlled
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

A-2: Unpaved roads/ Haul roads

- Implement traffic controls, including decreased speed limits, vehicle access restrictions and controls, road closures or barricades, off-road vehicle access control
- Pave using petroleum products (i.e., asphalts emulsions, etc.), asphaltic concrete, concrete
- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled *(use of water as the primary means of dust suppression for unpaved roads is discouraged)*
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

A-3: Paved roadways

- Perform scheduled vacuum street cleaning
- Clean up spillage and track out as necessary to prevent pulverized particulates from being entrained into the atmosphere

- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

B – Disturbed/Cleared Surface Area

B-1: Before active operations

- Plan work activities / timing of development to minimize disturbed / cleared areas
- Apply water if thoroughly controlled before active operations

B-2: During active operations

- Plan work activities / timing of development to minimize disturbed / cleared areas
- Install wind breaks or wind barriers
- Install partial or total enclosure systems
- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

B-3: Inactive period (temporary stabilization)

- Restrict access to the area
- Apply surface gravel
- Install ground cover (e.g., vegetative ground cover, tarps, plastic)
- Install wind breaks or wind barriers
- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled

B-4: Permanent stabilization of disturbed surface

- Restrict access to the area
- Pave
- Apply and maintain surface stabilization (e.g., gravel, other surface upgrade and stabilization)
- Restore area (e.g., revegetation)

- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled

C – Bulk Material Handling / Earthmoving

C-1: Hauling / Transporting

- Use properly secured tarps or covering to cover the load
- Prevent leakage from the truck bed, sideboards, tailgate, and bottom gate
- Limit load in vehicle
- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

C-2: Bulk material stacking, loading, and unloading operations

- Install wind breaks or wind barriers
- Apply dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

C-3: Active stockpile

- Restrict access to stockpiles areas
- Work under favorable meteorological conditions
- Limit stockpile height and slope
- Install wind breaks or wind barriers
- Cover exposed surfaces overnight or during periods of low excavation activity
- Install partial or total enclosure systems
- Use chemical stabilization with foaming agents in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions

- Apply other dust suppressants in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water if thoroughly controlled
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

C-4: Inactive stockpile

- Restrict access to stockpile areas to avoid unnecessary exposure and potential transfer of contaminantsInstall wind breaks or wind barriers
- Install removable ground cover (e.g., high-density polyethylene plastic liner)
- Install partial or total enclosure systems
- Install liners
- Use foam covering
- Use chemical stabilization (e.g., polymers, surfactants) to maintain a stable outer crust over stockpile
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

C-5: Active excavation site

- Plan work activities / timing of excavation activities to minimize soil disturbance
- Plan work to take place under favorable meteorological conditions
- Restrict access to the excavation areas to avoid unnecessary exposure and potential transfer of contaminants
- Install wind breaks or wind barriers
- Install partial or total enclosure systems
- Use foaming agents in amounts, frequency, and rates recommended by the manufacturer and compatible with site conditions
- Apply water with surfactants
- Apply water if water usage is thoroughly controlled and environmentally tolerable (i.e., sound knowledge of site conditions)
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

C-6: Inactive excavation site

- Restrict access to the excavation area to avoid unnecessary exposure and potential transfer of contaminants
- Install wind breaks or wind barriers
- Install ground cover (e.g., vegetative ground cover, tarps, plastic)
- Install partial or total enclosure systems

D - Demolition Activities

- Use curtains or shrouds Install partial or total enclosure systems
- Apply dust suppressants on the debris piles during demolition
- Apply water
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

E - General Construction/ Landscaping / Maintenance Activities

- Avoid clearing the entire site at once
- Install fencing
- Install partial or total enclosure systems
- Apply dust suppressants
- Apply water
- Cease operations; this may be considered as a contingency measure and may last as long as it takes to resolve and abate the dust control issues

Appendix G Control Monitoring Strategies

Dust control monitoring strategies include methods and actions that can be taken to meter application and monitor infiltration of dust suppression water, and to monitor airborne fugitive dust. Table G.1 lists these strategies. Monitoring strategies that are *always* recommended when there are sensitivities to groundwater protection at a specific site are marked by the icon. Additional information on theory and operation of the noted technologies follows.

Table G.1. Monitoring Methods for Dust Control Activities

Category	Description
Water Application Control	
Water Application Logs	Maintain a record of water application, including the number of times applied and daily total of water used (gallons), and document any incidents of water pooling or runoff, including the areas of the site affected. Record the manner of application (e.g., spraying or misting from stationary or vehicle-mounted spray system). For vehicle-mounted systems, record the calibrated application rate, vehicle speed, and boom pressure.
Water Truck/Spray System Metering	Use automated flow-based control systems or variable rate application systems to meter and control spray application of dust suppression water. Technologies are available for typical spray application systems and have been specifically developed to meter and control application rates of dust suppression water applied by water trucks.
Survey for Standing Water	During and after application of dust suppression water, visually survey the areas treated and note any instances of standing or pooled water or runoff as well as the affected areas of the site. Adjust water application rates and frequency to avoid creating pooled water, ponding, or runoff.
Near-Surface Soil Water and Infiltration	
Electrical Resistance / Heat Dissipation Blocks	Install electrical resistance blocks (gypsum or fiberglass) or heat dissipation units in the near-surface soil profile to monitor soil water contents. Sensors can be installed in areas receiving dust-suppression water, but where lead wires from the sensors will not be disturbed by vehicle traffic or construction/remediation activities.
Time-Domain Reflectometry (TDR)	Use hand-held TDR units to monitor near-surface soil water content at scheduled intervals or install TDR sensors that can be connected to data logging systems to monitor soil water content on a more frequent schedule (e.g., daily or hourly). If sensors are installed in the profile, the shallowest sensors should be placed deep enough in the soil to avoid compaction and disturbance (e.g., 20 to 30 cm below the surface) in areas receiving dust-suppression water. Lead wires from the sensors to the data logging system must be protected and/or buried so they will not be disturbed by vehicle traffic or construction/remediation activities.
Tensiometers	Use hand-held tensiometers to monitor near-surface soil water content at scheduled intervals or install tensiometers that can be connected to data logging systems to monitor soil water content on a more frequent schedule (e.g., daily or hourly). Tensiometers cannot be used where vehicle traffic or construction/remediation activities would destroy the equipment.
Neutron Probe Measurements	Install access ports with caps or water-proof covers/plugs in the near-surface soil profile where dust suppression water will be applied and in adjacent control areas that will not receive dust suppression water. Monitor near-surface water content at multiple depths (e.g., 0.5 m and 1 m) to detect differences in soil water content between water application areas and areas without water application.
Borehole Ground Penetrating Radar	Install ground penetrating radar equipment in existing monitoring wells to image sideways from the borehole to map soil-water content of surrounding subsurface.
Passive Capillary Lysimeters	Install passive capillary lysimeters in the near-surface soil profile to measure drainage in areas receiving dust suppression water. The access ports for drainage water removal must be protected from disturbance and damage from vehicles or construction/remediation activities.

Category	Description
Electrical Resistance Tomography (ERT)	Use surface-emplaced electrode arrays or electrode arrays placed in shallow boreholes to map dust-suppression water infiltration plumes and/or to monitor existing contaminant plumes.
GROUNDWATER/ PERCHED WATER TABLES	
Monitor Water Elevations in Nearby Downgradient Wells	Monitor the water elevation in nearby downgradient groundwater wells before and during the application of dust suppression water to detect changes in the water table elevation from increased water infiltration.
Monitor Dry Wells for Water	Monitor adjacent and downgradient dry wells to detect whether dust suppression water has infiltrated below the vadose zone.
ERT Detection of Perched Water	Use ERT or other geophysical methods to monitor the subsurface for formation of perched water tables resulting from the infiltration of dust suppression water.
AIR	
Visual Survey	Perform visual surveys for dust generation to determine whether dust suppression actions are necessary.
Meteorological Station/Anemometer and Vane for Wind Speed and Direction	Set up a meteorological station to monitor wind speeds and schedule dust-generating activities to minimize dust transport. Use other dust control strategies to minimize dust generation from stationary sources (such as stockpiles) when wind speeds are high.

G.1 Monitoring and Controls for Water Application Systems

The amount of water or water mixed with dust suppression chemicals used to control dust can be monitored or metered during application in several ways. Conventional sprayer systems can be set up to apply water or a chemical that is tank-mixed with a carrier (usually water) using spray nozzles and a pressure-regulating valve to provide a desired volumetric application of spray mix at a certain vehicle speed (Ess et al. 2001). The application rate depends on the flow from a nozzle, the sprayer travel speed, and the spray nozzle spacing, as shown in the following formula:

$$R\ (gpa) = \frac{Q\ (gpm)\ x\ 5{,}940}{S\ (mph)\ x\ W\ (in)}$$

where:

R = application rate (gallons per acre or gpa)
Q = flow from a nozzle (gallons per minute or gpm)
S = sprayer travel speed (miles per hour or mph)
W = nozzle spacing (inches)
5,940 = unit conversion constant

If the nozzle spacing is fixed, then the application rate can be changed by either changing the sprayer travel speed or changing the flow rate from the nozzle. Any change in the boom pressure or vehicle speed from that of the calibration results in an application rate different from the planned rate—basically a form of variable-rate application (VRA). Applicators can use this to address problem areas by manually increasing the pressure or reducing the speed to apply a higher (but somewhat unknown) rate.

Newer sprayer systems offer more automated controls of water or water plus chemical application rates. These include flow-based control systems and map-based or sensor-based VRA technologies (Grisso et al. 2011) as well as precision metering of water/chemical applications.

A typical flow-based control system combines a flow meter, a groundspeed sensor, and a controllable valve (servo valve) with an electronic controller to apply the desired rate of the tank mix. These types of systems include a microprocessor that uses information regarding sprayer width and prescribed application rate to calculate the appropriate flow rate (gallons per minute) for the current groundspeed of the spray vehicle. Based on the ground speed, the servo valve is opened or closed until the flow-meter measurement matches the calculated flow rate (Grisso et al. 2011).

Another way to control the flow is used in some large commercial-grade sprayers that are equipped with spray system pumps driven hydraulically at variable speeds. Pump output is directly controlled by varying the speed of a hydraulic motor used to drive the pump. Flow from the pump controls nozzle flow and the resulting application rates produced by such spraying systems (Ess et al. 2001).

Flow-based control systems have been developed specifically for dust control in the mining industry, where they are applied to provide precision metering for water truck systems. These water trucks are equipped with spray control systems that allow the operator to select a specific water application rate. The application rate is a user-designated value expressed as mm/m^2 and does not change regardless of ground speed, truck gear, and engine RPM that would normally affect the operation of the truck-mounted water pump and application rate. These systems avoid inadvertent over-application of water to the surface if vehicle speeds need to vary to accommodate rough surface conditions or additional traffic.[1]

Variable rate application technologies are flow-based control systems designed to control and modify the flow rate during application and change the amount of water or water and suppressant chemical to match either predetermined or real-time measures of surface conditions. Map-based VRA adjusts the application rate on the fly based on an electronic map, also called a prescription map. Using the field position of the water truck or spray system from a GPS receiver and a prescription map showing the desired application rates across the target area, the application rate can be changed as the spray system is moved through the target area. The map-based method can be implemented using a number of different strategies based on location-specific characteristics that can be delineated in the map: soil type, topography, remotely sensed imagery are examples (Grisso et al. 2011).

Sensor-based VRA technologies enable the application rate to be varied without prior mapping or data collection. Real-time sensors measure the specified surface properties—such as soil properties, topography, or surface characteristics—while on the go. Measurements made by such a system are then processed and used immediately to control a variable-rate applicator. Using real-time sensor methods for VRA doesn't necessarily require the use of a positioning system, nor does it require extensive data analysis of the target area before making variable-rate applications; however, if the sensor data are recorded and geo-referenced, the information can be used in future site-specific management for creating a prescription map for an "as applied" application record.

[1] A number of companies provide systems that incorporate these technologies to control the amount of water applied. Examples can be found at the following links. Inclusion here does not imply any recommendation or endorsement of any particular system or company:
https://www.megacorpinc.com/page.asp?p_key=E533BADE3624439D8AEB34768D6DD59F
https://abcdust.net/smartwatertrucksystems/
https://www.cat.com/en_US/articles/solutions/oem-solutions/manage-your-haul-roads-with-the-cat-water-delivery-and-control-system.html

G.2 Technologies for Monitoring Near-Surface Soil Water and Drainage

Monitoring the amount of water in near-surface soils can help determine whether dust-control water applications will potentially exceed the surface soil capacity to store water and cause dust suppression water to infiltrate and drain through the profile. When the soil water content exceeds the capacity of the soil to hold water, water freely infiltrates deeper into the soil profile. Application of dust suppression water in amounts that exceed the water-holding capacity of the near-surface soil profile potentially can cause water to drain through the profile and increase recharge.Table G.2 illustrates examples of common field capacity values (an indication of the water holding capacity) for different soil textural classes (Panuska et al. 2015). A number of commercially available sensors and technologies have been developed to monitor near-surface soil moisture and provide information that could potentially be used to monitor dust-control water application.

Table G.2. Examples of Field Capacity[a] by Soil Texture Class

Soil Texture	Field Capacity (% by volume)
Sand	9
Loamy Sand	13
Sandy Loam	21
Loam	27
Silt Loam	33
Sandy Clay Loam	26
Clay Loam	32
Clay	40

(a) The content of water, on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible (Soil Science Glossary Terms Committee 2008).

Soil moisture sensors can be stationary units installed at fixed locations and depths, or some technologies can be employed as portable handheld probes. Common soil moisture monitoring technologies that could be installed to monitor near-surface soil moisture include electrical resistance blocks, heat dissipation blocks, tensiometers, and dielectric methods such as TDR. These sensor systems must be properly installed with good contact with the soil and placed in locations that are representative of the overall condition of the region to be monitored. Installation of the sensors to monitor changes in soil moisture due to water application would require placing sensors in the areas where water will be applied, but where sensors will not be disturbed or crushed by tires, blading/grading, or other vehicle and construction activities.

Neutron probes are portable readout units but require installation of monitoring tubes at fixed locations. Handheld tensiometers and portable handheld TDR units can be carried to particular sites of interest and inserted into the soil, and provide a readout showing soil moisture conditions in moist soils.

Commonly available soil moisture sensors quantify soil moisture in terms of soil water content or soil water potential:

- Soil water content is the amount of water in a known amount of soil and is expressed as percent water by weight (gravimetric) or percent water by volume (volumetric).

- Soil water potential (or soil water tension) is a measurement of how tightly water clings to the soil and is expressed in units of pressure [kilopascals (kPa), megapascals (MPa), bar or centibar]. The drier the soil, the greater the soil water potential (tension). Soil water potential may be expressed as either a positive or negative number (larger negative values indicate greater tension and drier soils).

Determining which sensors to use in monitoring applications requires knowledge of the theory of operation, the limitations of the technology, and whether monitoring data will be used as a qualitative or quantitative measure to assess infiltration and drainage. It also requires an understanding of how the monitoring data/information will need to be processed or managed to adequately assess soil water changes and infiltration through the soil profile. It may be advisable to solicit input from subject matter experts with experience in monitoring water in the vadose zone at Hanford to help design and implement a monitoring strategy. The following subsections provide additional information regarding the principles of operation and strengths and weaknesses of readily available sensors/technologies for monitoring soil moisture in the near-surface vadose zone.

G.2.1 Electrical Resistance Blocks

Electrical resistance blocks are porous blocks typically made from gypsum, fiberglass, or ceramics, which are buried in the soil. As water moves into or out of the material, an equilibrium is reached between water absorbed in the block and water in the soil. Each block contains electrodes that are used to record the electrical resistance between the electrodes, which is related to the moisture content of the soil. Some of the most common electrical resistance blocks are constructed of wires or a wire grid embedded in a gypsum material. The block may be entirely gypsum or covered with a porous material such as sand, fiberglass, or ceramic. Lead wires reaching from the buried electrical resistance block to the soil surface are available in various lengths. A portable conductance meter is attached to the wires at the surface to read the electrical resistance of each block. The drier the soil, the greater the electrical resistance.

Blocks are generally calibrated to measure soil water potential with a measurement range for gypsum blocks between 0.3 and 2.0 bar; nylon and ceramic blocks may have a slightly larger range. The readings are temperature dependent (up to 3% change/°C) and field-measured resistance should be corrected for differences between calibration and field temperatures. Some reading devices have manual or self-compensating features for temperature, or the manufacturer may provide correction charts or equations. These blocks can deteriorate over time, and in wet soils may be useful for only one season. Soil-moisture blocks are generally considered most dependable in the low-moisture-content range, below field capacity. Under these conditions, the fiberglass blocks normally have a greater range of operation than the gypsum blocks. At higher moisture contents, between field capacity and saturation, the change in resistance per unit change in moisture content is small, thus reducing the sensitivity of the units. Problems may also occur with highly acid or highly saline soils. Accuracy is generally low but can be improved by soil-specific calibrations.

Electrical resistance blocks are often used to detect the arrival and duration of a wetting front infiltrating through the soil. As part of the monitoring program, one option might be to place blocks within the top meter of soil in the dust control water application area (but below or outside the zone expected to be disturbed or disrupted by construction/driving/excavation potential disturbances) and compare the measurements with blocks similarly placed in the profile outside the area of water application.

G.2.2 Heat Dissipation Blocks

Heat dissipation sensors work on the principle that the thermal conductivity of water influences dissipation of heat—that is, dry soil will heat faster than wetter soils. In other words, the heat flow in a porous material (soil) is proportional to the water content of that material (Munoz-Carpena 2018). They can be used to infer soil matric potential from previously determined soil-specific calibration relations between sensor heat dissipation and soil matric potential.

The sensor consists of a porous block containing a heat source and an accurate temperature sensor. The block temperature is measured before the heater is powered and after the heater is powered for a few seconds. The porous block, placed in contact with the soil, is equilibrated with the soil matric potential rather than a water-content equilibrium; therefore, the measured heat dissipation is related to the matric potential of the soil through laboratory calibration. Because water and solutes exchange freely between the sensor and the soil, heat dissipation sensors measure matric potential rather than total water potential.

G.2.3 Tensiometers

Tensiometers consist of a simple tube (usually of metal or non-porous plastics) with a porous cup at the lower end. The tube is filled with water, sealed airtight, and installed in soil; as the soil dries, the water is pulled from the porous cup into the soil until the moisture in the soil reaches an equilibrium with the moisture in the porous cup. This creates a vacuum, and a measurable tension or suction in the tube holding the water column, which is equivalent to the soil water potential. Some tensiometers are equipped with rubber septa at the top of the tube where a needle can be inserted to enable measurement, and some include a negative pressure (vacuum) gauge on top designed to measure the soil water tension or soil water potential. The range of measurement is limited to fairly wet soil conditions—in dry soils, the water is pulled from the porous cup and cannot achieve equilibrium with soil water, so air leaks into the system, causing erroneous readings. Tensiometers are best suited for measuring soil moisture in fine soils with good contact between the porous cup and the soil. Tensiometers usually are not recommended for measuring soil water conditions in sandy or clayey soils or where soils are seasonally dry.

G.2.4 Neutron Probe Measurements

A neutron probe uses a radioactive source and detector for measuring soil moisture. The probe containing the source is lowered into a tube, usually made of 2-inch inside diameter PVC or aluminum, installed in soil to a depth of interest. Neutrons are emitted from the source and slow down and are scattered back when they collide with hydrogen in the soil water (H_2O). The detector monitors the flux of slow neutrons scattered by the soil water and correlates this measurement to soil water content. Neutron probes are accurate when properly calibrated but must be calibrated for each soil type. The system is not influenced by salts, has a large radius of measure (10 inches in diameter around the probe), and can take measurements at many depths. However, a number of factors may constrain use for monitoring dust suppression:

- Neutron probes are relatively expensive.
- Use of the probe requires installation of monitoring ports in representative areas.
- The instrument poses a radiation hazard (requires certified personnel), so the presence of a radioactive source triggers requirements for operators to be trained and licensed in handling, storage, transportation, and use.
- Calibration of the probe for individual soil types can be difficult.
- Measurements close to the soil surface are not as accurate because neutrons escape to the atmosphere and are not detected.

These constraints, and particularly the lack of accuracy near the soil surface (top 20 cm), likely make the neutron probe a less useful measurement tool for most applications that need to monitor near-surface soil moisture for dust control. However, use of these instruments can provide information about movement of wetting fronts through the near-surface vadose zone.

G.2.5 Dielectric Methods

Dielectric soil sensors measure the dielectric constant of the soil, which depends on soil moisture (the dielectric constant is about 1 in air; 3 to 5 in soil; and around 80 for water). Changes in soil moisture cause significant changes in the dielectric constant of the soil, and the dielectric methods described here use empirical calibrated relationships between volumetric water content and the sensor output signal (time, frequency, impedance, wave phase) (Munoz-Carpena 2018). Typical sensors include capacitance sensors and TDR sensors, which are electronic devices that can be either portable or stationary. They read instantly and can accurately measure over a wide range of soil textures and moistures. Calibration equations relating the dielectric constant to the soil moisture content are generally provided by the manufacturer, but soil-specific calibrations may be required for monitoring applications to reduce errors in measurement.

Capacitance sensors consist of two electrodes separated by a material that does not readily conduct current termed the dielectric. They can be constructed to use a pair of stainless-steel rods, called wave guides, inserted in the soil or a single-piece insert inserted in the soil. Multiple capacitance sensors can also be fully contained within a PVC pipe installed vertically in the soil to record soil moisture at multiple depths. When the sensor is inserted into the soil, it becomes part of the dielectric. An oscillator applies a specific frequency to the sensor's electrodes, which causes a resonant frequency in the soil. The magnitude of the frequency depends on the dielectric constant of the soil, and the greater the soil moisture content, the smaller the frequency. The sensors can be read with a handheld electronic readout unit or connected to a data logger with the appropriate calibration to record percent volumetric soil moisture.

TDR sensors typically use two or three steel rods, called waveguides, installed in the soil parallel to one another. The TDR system includes a voltage pulse generator, a signal analyzer, the waveguides, and a cable connecting the waveguides to the instrument. An electrical pulse is applied to the wave guides and the time needed for the electrical pulse to travel to the end of the waveguide and be reflected back is measured. The travel time required for the pulse to reach the end of the waveguides and return back depends on the dielectric constant of the soil; the larger the dielectric constant, the longer the travel time. The sensors can be read with a handheld electronic readout unit or connected to a data logger with the appropriate calibration to record percent volumetric soil moisture.

G.2.6 Monitoring Drainage

Measuring water flow rates and drainage in the vadose zone is difficult. Lysimeters are one of the few technologies that can be installed to provide a direct measure of water flux in the vadose zone below the zone of evaporation and transpiration demands (Allen et al. 1991). For this purpose, a lysimeter consists of a container of soil buried at depth that intercepts and captures water draining through the profile, and the drainage volume is measured over time. The various types of lysimeters that have been used to measure drainage include pan lysimeters, equilibrium tension lysimeters, and wick lysimeters. Pan lysimeters collect only free drainage water and are sometimes called "zero tension" lysimeters, while tension lysimeters and wick lysimeters collect water under tension, either through a vacuum control system or applied via a hanging water column (i.e., wick) (Gee et al. 2009).

Of these, the passive wick lysimeter, often called a passive capillary lysimeter, is likely the best method for use in monitoring drainage from dust control water applications based on costs and simplicity of the measurement system. Commercially available units consist of a stainless steel or PVC divergence control tube that holds the soil monolith. Water infiltrates down through the soil and enters the divergence control tube, then flows down through a wick into a reservoir. Current designs use a duct and wick design to keep the soil tension in the soil column similar to that of the natural soil at the installation site. The lysimeter tube is installed at a depth below the zone where transpiration and evaporation remove water from the soil. The collected drainage water stored in the reservoir below the lysimeter is removed through a surface port. Add-on sensors can be used measure conductivity, temperature, and depth of the collected sample and to help determine when to empty the sample reservoir. The sensor package can also provide time-series drainage data. The sensor package requires power, and data can be read using several commercially available data logging systems.

G.2.7 Electrical Resistivity Tomography

Electrical resistivity tomography is a geophysical technique for measuring lateral and vertical variation of subsurface electrical resistivity and can be used to investigate flow processes in both the saturated and unsaturated zones. ERT uses a large number of resistance measurements taken from an array of electrode pairs installed on the soil surface or in boreholes to calculate the subsurface distribution of electrical resistivity. It can be used to monitor soil water content and hydraulic conductivity through time, and the resistance distribution data can be used to map water infiltration and plume migration.

Two-dimensional and three-dimensional electrical tomography surveys place a large number of electrodes in the soil area of interest. Electrodes are placed on the ground surface or in boreholes in geometric patterns to make the resistance measurements. Electrical current is introduced into one electrode pair while the resulting voltage change is detected between electrode pairs in the array similar to a surface dipole-dipole array. These data are topographically inverted to image resistivity contrasts, and the spatial distribution and temporal changes in resistivity can be used to map water content or map infiltrating water in space and time.

Although ERT can be applied to develop a spatial understanding of infiltration and soil water status, setting up and operating ERT arrays for monitoring hydrologic and geologic conditions requires significant technical expertise and an in-depth understanding of the soils and geology of the area to be monitored. As described by Daily et al. (2005), calculating each resistivity image using ERT data requires carrying out an inversion procedure that produces a model (i.e., a spatially varying distribution of resistivity) that has an acceptable fit to the data and satisfies prescribed constraints. The complexity of data analysis and expense associated with setup and operation may be prohibitive for monitoring the application of dust suppression water in most situations. However, in cases where water applications exceed the thresholds for limiting infiltration and the potential for contaminant mobilization exists, these technologies may be applicable.

G.3 Groundwater and Perched Water Table Monitoring

In areas where the water applied for dust suppression could infiltrate and potentially cause mobilization of contaminants, it may be prudent to monitor the water levels in existing groundwater monitoring wells adjacent to the water application areas and in groundwater wells that are downgradient of water application areas. Monitoring the water level in adjacent wells likely could require modifications or additions to routine scheduled groundwater monitoring surveys. More frequent monitoring of water-level elevations may be accomplished by installing automated water-level monitoring equipment. Some wells within the Hanford Central Plateau are already equipped with automated water-level monitoring equipment—about 4%. Water-level monitoring and data interpretation at Hanford should be coordinated with the Hanford Groundwater Monitoring Program.

Perched water tables resulting from the application of dust-suppression water could potentially be identified in several ways. Dry wells in the project vicinity and downgradient of the water application should be monitored before project activities begin and on an appropriate schedule during and after the application of dust-suppression water. ERT may also be employed to detect suspected formation of a perched water table.

In areas where groundwater monitoring wells are distant, or when the risk of contaminant mobilization due to application of dust-suppression water is high, geophysical methods such as ERT could be employed to monitor for the formation of perched water tables or groundwater mounds.

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Appendix H – Defining the Appropriate Dust Control Monitoring Strategy

Determining which approaches to use for monitoring dust control applications is dependent on both site-specific properties (e.g., the risk of accelerating subsurface contaminant migration) and resource availability. If more sophisticated methods are selected, the installation and operation of monitoring equipment should be done in consultation with subject matter experts with technical expertise in the chosen system. Selecting and implementing a monitoring strategy may also require consultation and coordination with existing Hanford Site monitoring programs. Surveillance and monitoring of groundwater elevations, subsurface contaminants transport, and air monitoring for contaminants are routinely done by the Hanford Site contractors. Project-specific monitoring strategies for these media and scheduling of monitoring activities should be coordinated with the appropriate Hanford Site monitoring programs.

At a minimum, visual surveys will be needed to confirm that air quality is protective of human health and ponding is not occurring on the ground surface. Metering the application of dust-suppression water is highly recommended to ensure that the amount of water applied does not exceed maximum limits. Monitoring groundwater elevations in nearby wells is recommended to verify that dust suppression water is not infiltrating to groundwater. For sites with known underlying contamination, more sophisticated moisture monitoring of near-surface soils may help determine the degree of drainage occurring.

Table H.1 provides information on the relative costs of implementing different types of technologies and equipment for monitoring. Actual costs of monitoring will depend on the monitoring strategy employed and site-specific characteristics (including size of area to be monitored) and project-specific requirements.

Table H.1. Relative Costs of Dust-Control Monitoring Strategies

Strategy	Relative Cost			Basis
	Low	*Medium*	*High*	
Dust Monitoring				
Visual Survey	X			Labor costs for staff to perform and document survey.
Meteorological Station/Anemometer and Vane for Wind Speed and Direction	X	X		Purchase of commercially available station and labor costs for maintenance, operation, and documentation.
Water Application Controls				
Survey for Standing Water	X			Labor costs for staff to perform and document survey.
Water Application Logs	X			Labor costs for staff to fill out logs on regular schedule.
Water Truck/Spray System Metering	X	X		Actual costs dependent on type and calibration requirements of water application system.
Near-surface Soil Water and infiltration				
Electrical Resistance/Heat Dissipation Blocks	X	X		Costs for data logger/electronic readout system and limited number of sensors (<20) expected to be $1000-$2000. Actual costs dependent on design and number of sensors required.
Time-Domain Reflectometry	X	X		Costs for one data logger/electronic readout system and limited number of sensors (<20) expected to be $1000-$3000. Actual costs dependent on design and number of sensors required.
Tensiometers	X			Costs for data logger/electronic readout system and limited number of sensors (<20) expected to be $1000-$2000. Actual costs dependent on design and number of sensors required.
Neutron Probe	.	X	X	Probe costs estimated between $5000 and $15000 plus labor costs to install access wells.
Borehole Ground Penetrating Radar				
Passive Capillary Lysimeters	X	X		Costs assumed to be ≤$1000 per unit plus labor costs to install and sample drainage volume periodically.
Electrical Resistance Tomography (ERT)	.		X	Costs anticipated to range from $50,000 to more than $100,000 depending on area to be monitored, complexity of array and frequency of data collection.
Groundwater/ Perched Water Tables				
Monitor Water Elevations in Nearby Downgradient Wells	X	X		Labor costs to schedule and monitor water table elevation in wells. Actual costs dependent on number of wells monitored.
Monitor Dry Wells for Water	X			Labor costs to schedule and monitor water table elevation in wells. Actual costs dependent on number of wells monitored.
ERT Detection of Perched Water			X	Costs anticipated to range from $50,000 to more than $100,000 depending on area to be monitored, complexity of array, and frequency of data collection.

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