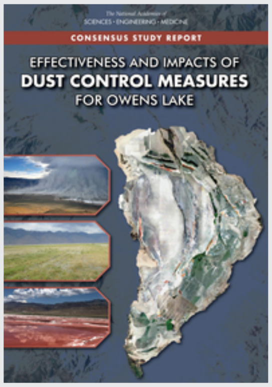

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EFFECTIVENESS AND IMPACTS OF **DUST CONTROL MEASURES** FOR OWENS LAKE

Owens Lake Scientific Advisory Panel

Board on Environmental Studies and Toxicology

Board on Earth Sciences and Resources

Water Science and Technology Board

Division on Earth and Life Studies

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In the course of preparing its report, the Owens Lake Scientific Advisory Panel (OLSAP) held public information-gathering sessions during two meetings and three web conferences to hear presentations from representatives of Air Sciences, Inc., Big Pine Paiute Tribe of Owens Valley, California Department of Fish and Wildlife, California State Lands Commission, Eastern Sierra Audubon, Great Basin Unified Air Pollution Control District, Lone Pine Paiute-Shoshone Reservation, Los Angeles Department of Water and Power, and Ramboll. OLSAP gratefully acknowledges the individuals listed in Appendix B for their presentations during the information-gathering sessions. In addition, OLSAP is grateful to the many individuals who arranged for the three field-trip sessions at Owens Lake and provided written materials in response to panel requests.

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **Deb Niemeier**, University of California, Davis, and **Thure Cerling**, University of Utah. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Abbreviations and Acronyms

AF	acre-feet
BACM	Best Available Control Measure
CAA	U.S. Clean Air Act
CARB	California Air Resources Board
CDFW	California Department of Fish and Wildlife
CE	control efficiency or control effectiveness
CEQA	California Environmental Quality Act
CFR	Code of Federal Regulations
DCMs	dust control measures
ECR	Eligible Cultural Resource
EPA	U.S. Environmental Protection Agency
FAO	Food and Agricultural Organization
FEM	Federal Equivalent Method
FRM	Federal Reference Method
GBUAPCD	Great Basin Unified Air Pollution Control District
GWC	gravimetric water content
LADWP	Los Angeles Department of Water and Power
MSAs	Metropolitan Statistical Areas
NAAQS	National Ambient Air Quality Standards
NDD	normalized distance downwind
OLSAP	Owens Lake Scientific Advisory Panel
OVPA	Owens Valley Planning Area
PM_{10}	particulate matter 10 micrometers or less in diameter
$PM_{2.5}$	particulate matter 2.5 micrometers or less in diameter
PV	photovoltaic
SFWCRFT	Shallow Flood Wetness Cover Refinement Field Testing
SIP	State Implementation Plan
SWEEP	Single-Event Wind Erosion Evaluation Program
TEOM	Tapered Element Oscillating Microbalance

Contents

Summary

During the 20th century, the city of Los Angeles diverted surface water flowing into Owens Lake for water supply, transforming the large, closed-basin, saline lake into a small brine pool surrounded by dry playa. Under high winds, the exposed lakebed produced large amounts of airborne dust, resulting in the highest concentrations of airborne particulate matter with an aerodynamic diameter of 10 micrometers or less (PM_{10}) in the United States. Since 2000, the Los Angeles Department of Water and Power (LADWP), at the direction of the Great Basin Unified Air Pollution Control District (District), has been constructing and implementing dust control measures (DCMs) on the dry lakebed, with the objective of meeting the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) for PM_{10} and the PM_{10} standards set by the state of California. LADWP reported that it has spent $2.1 billion on dust control efforts as of May 2019 and that many of the DCMs require large amounts of water, energy, and maintenance to sustain their performance.[1] Shallow flooding is, by far, the most widespread DCM, by surface area, that is applied at Owens Lake. Other DCMs, such as managed vegetation and gravel, are also applied over several areas on the lakebed, and a few small areas ordered for PM_{10} management are currently uncontrolled. On average since 2007, water use for dust control required 31 percent of LADWP's fresh water supplies available at Owens Lake, [2] with a range of 17 to 51 percent.

In 2014, a Stipulated Judgment agreed to by LADWP and the District[3] ended litigation concerning dust control requirements and acknowledged the need "for additional effective DCMs that do not rely on water that can be substituted in areas currently under control or applied in areas ordered to be controlled." The Judgment also acknowledged "the need to

[1] Prior to LADWP's launch of dust mitigation projects in 2000, the District conducted research and testing of DCMs in the 1980s and 1990s.

[2] Available water is assumed to be the sum of LADWP exports in the Los Angeles Aqueduct and Owens Lake freshwater use for dust control. See Chapter 3.

[3] Stipulated Judgment in the matter of the City of Los Angeles v. the California Air Resources Board et al. Superior Court of the State of California, County of Sacramento. Case No. 34-2013-80001451-CU-WM-GDS. Approved by the court on December 30, 2014. See https://gbuapcd.org/Docs/District/AirQualityPlans/SIP_Archive/2014_Stipulated_Judgment_20141230.pdf (accessed January 28, 2020).

balance the requirements to control dust emissions and conserve water with the requirements to minimize impacts to cultural and biological resources." As part of the Judgment, LADWP and the District agreed to contract with the National Academies of Sciences, Engineering, and Medicine to establish the Owens Lake Scientific Advisory Panel (OLSAP, or the panel) to provide ongoing advice on the reduction of PM_{10} in the Owens Valley. In addition, the Judgment intends the panel to foster communication and collaboration between the LADWP and the District within this context.

The panel's first task is to evaluate the effectiveness of alternative DCMs for their dust control and water use. The task includes consideration of the associated energy, environmental, and economic impacts and assessing the durability and reliability of such DCMs (see Box S-1).

In interpreting its task, the panel was informed by the definition of environment provided in the California Environmental Quality Act (CEQA), which encompasses impacts on land, air, water, minerals, flora, fauna, ambient noise, and objects of historical or aesthetic significance. The panel discussed key factors within the broad context of that definition with implications for dust management. The panel assessed 15 DCMs (see Box S-2) that represent a range of mitigation approaches that are either being applied at Owens Lake or at various stages of development.

Box S-1
Statement of Task

The Owens Lake Scientific Advisory Panel (OLSAP) is being established in response to a request from the Great Basin Unified Air Pollution Control District (GBUAPCD) in California and the Los Angeles Department of Water and Power (LADWP) to evaluate, assess, and provide ongoing advice on the reduction of airborne dust in the Owens Valley in California. The request to establish OLSAP is pursuant to a Stipulated Judgment that LADWP and GBUAPCD entered into in 2014.[a] The National Academies will establish, staff, and administer OLSAP according to institutional policies and procedures.

As indicated in the 2014 Stipulated Judgment, OLSAP's first task will be to evaluate the effectiveness of alternative dust control methodologies for their degree of PM_{10} reduction at the Owens Lake bed and to reduce use of water in controlling dust emissions from the dried lakebeds. (PM_{10} refers to airborne particulate matter with an aerodynamic diameter of 10 micrometers or smaller.) The evaluation should consider associated energy, environmental and economic impacts, and assess the durability and reliability of such control methods.

[a] Stipulated Judgment in the matter of the City of Los Angeles v. the California Air Resources Board et al. Superior Court of the State of California, County of Sacramento. Case No. 34-2013-80001451-CU-WM-GDS. Approved by the court on December 30, 2014. See https://gbuapcd.org/Docs/District/AirQualityPlans/SIP_Archive/2014_Stipulated_Judgment_20141230.pdf (accessed January 28, 2020).

Box S-2
Dust Control Measures

Current Best Available Control Measures (BACMs) and Approved BACM Modifications[a]

- Shallow Flooding:
  - *Shallow Flooding:* Use of standing water applied onto a dry lakebed during the dust season.
  - *Dynamic Water Management:* An operational modification of shallow flooding that allows for later start dates and/or earlier end dates to reduce water use.
  - *Brine with Shallow Flooding Backup:* Application of brine and/or development of a thick salt crust to stabilize the surface.
  - *Tillage with Shallow Flooding Backup:* Use of mechanical methods to create a series of plowed ridges and furrows, generally oriented perpendicular to the predominant winds to enhance roughness and reduce near-surface winds.
- *Managed Vegetation:* Planting of locally adapted, native vegetation in a dust control area.
- *Gravel:* A zero-water control measure that involves the placement of a layer of gravel on the surface or on top of a permanent permeable geotextile fabric.

Other Dust Control Measures

- *Cobbles:* Similar to the gravel dust control measure, except the sizes of the stones are larger, on average, and more heterogeneous.
- *Sand Fences:* Vertical barriers up to about 5 feet in height used to control movement of windblown sand.
- *Precision Surface Wetting:* Use of reciprocating sprinklers or perforated whip lines to wet circular areas of the lakebed to maintain a targeted wetted percentage of the soil.
- *Artificial Roughness:* Engineered or natural material (porous or solid) placed in arrays on the surface of a control area.
  - *Porous engineered* material (such as cubes or cylinders) usually with a designed geometry and porosity.
  - *Solid engineered* material, such as solid-walled plastic bins.
  - *Porous natural* material (such as dead woody vegetation) that can be applied in natural clumps.
  - *Solid natural* material, such as straw bales or boulders.
- *Shrubs:* A modification of the managed vegetation control measure that uses shrubs with the intent of needing less vegetation cover and less water relative to other plants to achieve a desired dust control level.
- *Solar Panels:* Photovoltaic panels deployed for electricity production that also serve to reduce ground-level wind speeds.

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[a] The District, in concurrence with the U.S. Environmental Protection Agency, determines dust control measures to be BACMs for use on Owens Lake (see Chapter 4 for more discussion of current BACMs).

The panel's evaluation criteria included reported PM_{10} control efficiency, water use, capital and operating costs, habitat value, protection of cultural resources, durability, reliability, and other factors.

Because quantitative data were not available in many cases, the panel also used semi-quantitative and qualitative approaches to evaluate the DCMs, as necessary.

OVERALL CONCLUSION

DCMs applied at Owens Lake during the past 20 years have significantly reduced PM_{10} concentrations in the Owens Valley, although further progress in controlling dust is needed to meet air quality standards. The panel evaluated 15 DCMs based on their potential effectiveness in reducing PM_{10} emissions, water use, and environmental impacts. Based on available data, none of the control measures has been documented to achieve mandated levels of dust control while substantially reducing water use (compared to shallow flooding) and consistently providing quality habitat, although some measures show promise with the need for additional research and testing. Progress toward these multiple goals, including protection of environmentally sensitive areas by reducing land disturbance from DCMs, can be more effectively achieved through a systems approach that considers outcomes over a large spatial scale and interactions among control measures. To inform these decisions, additional research is needed on individual and hybrid DCMs and on the landscape-scale effects of dust control configurations. Evaluation of operational performance of DCMs should be based on airborne PM_{10} measurements rather than surrogate measures, such as the percentage of a control area that must be covered by vegetation or surface water. Using a systems approach and evaluating DCM performance with PM_{10} measurements would promote innovative and hybrid strategies for dust control.

PROGRESS IN MANAGING AIRBORNE PM_{10}

Because of the implementation of DCMs on Owens Lake by the District and LADWP, airborne PM_{10} concentrations at monitoring locations in the Owens Valley Planning Area have decreased significantly. The number of days that near-lake monitors had exceedances of the NAAQS for PM_{10} decreased from 49 days in 2002 to 8 in 2018 (the last full year for which data were available at the time of this report). The maximum 24-hr average PM_{10} concentration decreased from 20,750 micrograms per cubic meter ($\mu g/m^3$) in 2001 to 728 $\mu g/m^3$ in 2018. The average NAAQS exceedance PM_{10} concentration has also decreased from more than 1,000 $\mu g/m^3$ in 2000 to fewer than 241 $\mu g/m^3$ in 2018. Based on monitoring data from January to June 2019, 4 days had NAAQS exceedances. The maximum exceedance concentration during that period was 451 $\mu g/m^3$, and the average exceedance concentration was 280 $\mu g/m^3$.

The reductions in PM_{10} concentrations are evidence of the general effectiveness of DCMs implemented on Owens Lake. However, additional progress is needed to meet the NAAQS, which require that daily average PM_{10} concentrations not exceed 150 μg/m^3 more than an average of once per year over a 3-year period. Meeting the air quality standard imposed by the state of California (maximum daily average PM_{10} concentrations not to exceed 50 μg/m^3) would require even greater emission reductions than for meeting the NAAQS. Although further DCMs will be needed for on-lake sources, off-lake sources (mostly located near the lakebed) continue to challenge the ability to attain the PM_{10} air quality standards within the Owens Valley Planning Area (the southern Owens Valley, where Owens Lake is situated).

NATURAL RESOURCES AND ENVIRONMENTAL CONTEXT FOR DUST CONTROL

Precipitation and water runoff in the Owens Valley are highly variable, which creates significant challenges for dust management and affects available water supplies for export through the Los Angeles Aqueduct. From 1950 through the mid-1980s, the aqueduct consistently provided at least 300,000 acre-ft/year, with even greater production in the 1970s and early 1980s from groundwater pumping and water diversions. Since about 1994, exported flows have averaged 250,000 acre-ft/year, with wide interannual variability. In the past decade, water exports have been significantly reduced (averaging approximately 170,000 acre-ft/year) because of California's multiyear drought and water needed for dust control at Owens Lake. The 2012-2016 drought required significant changes in both the operation of the aqueduct and dust mitigation strategies. Extreme precipitation has also stressed the ability to manage dust on the lakebed. For example, heavy snow and rapid melt in 2017 threatened to flood portions of the dust control infrastructure and mining operations on the lake.[4]

Climate change is anticipated to adversely impact the Owens Valley water supply and therefore dust control efforts, with longer and more severe droughts and more extreme wet years. Those expected trends will likely reduce the reliability of DCMs that involve the use of large amounts of water. Rising temperatures are also expected to increase evaporation at Owens Lake and thereby increase the demand for water that is used for dust control. At the same time, higher temperatures will reduce average runoff in the Owens Valley, because of increased transpiration by plants and evaporation at higher elevations. Warming temperatures are also likely to increase the dominance of rain over snow in the headwaters of the Owens River watershed, leading to more rapid runoff and increases in spring peak runoff. **Because of climate-related changes, the availability of water for dust mitigation will be more variable, more water will be needed during dry periods to mitigate dust and maintain habitat, and more pressure will be put on the system to support downstream water demands.**

Dust control efforts at Owens Lake have created a variety of habitats on the lakebed, including now regionally rare habitats such as alkaline meadows and shallow flooded areas.

[4] Ore deposits of trona (a salt consisting of sodium carbonate and sodium bicarbonate) are mined at Owens Lake (see Chapter 3).

The diversity of birds supported by those habitats is based on the engineered conditions that vary in water depth, salinity, and surrounding environs. Because highly productive food webs tend to occur in brackish pools, long-term salinity management to maintain these habitats is particularly important. While management of habitats across broad regions will become more challenging under climate change because of habitat loss and effects on breeding and food availability, the habitats provided by Owens Lake will become more critical to local and regional conservation, particularly because saline lake bird habitat elsewhere within the Great Basin is shrinking. In fact, Great Basin shorebird populations have already decreased by 70 percent over the past few decades.

To date, bird populations and habitat have received the most attention, but dust control can be a valuable conservation tool for providing habitat for diverse species. **The value of diverse, aquatic and non-aquatic habitats and the relative abundance of those habitats in the Owens Valley are important considerations when setting priorities for lake-wide management decisions.**

Local Native American tribes are an integral part of the environment and have a strong sense of ownership and stewardship of land in the Owens Valley. **Local tribes have expressed concerns about the potential damage to culturally and historically significant sites from the use of heavy machinery and levelling operations typically used during DCM construction. Tribal concerns also include preservation of the natural landscape, because many topographic features and types of ecosystems are highly valued.**

EVALUATION OF DUST CONTROL MEASURES

Based on available data, none of the current Best Available Control Measures (BACMs) or other DCMs has been documented to achieve mandated dust control efficiencies, while substantially reducing water use (compared to shallow flooding) and consistently providing moderate or high habitat values. Of the DCMs reviewed, many involved a high level of land disturbance and infrastructure that could impact cultural resources in environmentally sensitive areas, although a few could be conducted with low land disturbance. Using a variety of data, the panel evaluated 15 DCMs—including approved BACMs and BACM modifications and other DCMs in various levels of testing—for their PM_{10} control, water use, cost, ability to provide habitat, and other factors, such as the extent of land disturbance and aesthetics. However, the panel did not presume to understand many of the factors that influence the acceptability of a DCM in environmentally sensitive areas. As described in Chapter 4 and summarized in Table 4-1, its findings reveal that no control measure met desired performance in all categories.

Of the DCMs reviewed, precision surface wetting, shrubs, natural porous roughness, and cobbles appear to be promising strategies, individually or in combination, for substantially reducing water use and providing some habitat value (see Chapter 4). For example, field tests suggest that precision surface wetting may be able to provide mandated control efficiency with reduced water use compared to shallow flooding, and refined configurations offer potential for further reduced water use. The habitat supported by sprinkler irrigation at the test site is similar to that of alkaline meadows, which are regionally rare. However, some amount of shallow flooding is needed to support habitat for shorebirds and Snowy Plover—a species of high conservation value regionally. The use of shrubs as an alternative DCM is promising with lower vegetation cover and water use than currently required by the managed vegetation BACM. Shrubs may not be able to provide mandated control efficiency under entirely rain-fed conditions, but the alternative measure may provide a useful option with some supplemental irrigation or in locations where reduced control efficiencies are allowed. Cobbles and natural porous roughness are promising waterless approaches that have not been tested at Owens Lake and deserve additional attention. Cobbles theoretically offer improved dust control and aesthetics compared to gravel, while allowing native vegetation growth. Natural porous roughness offers improved aesthetics compared to engineered roughness and moderate-value habitat. Initial testing of a solar photovoltaic installation on top of a gravel layer revealed mixed results, but solar panels have dust control potential that could be investigated further, with or without placing the panels on top of a gravel layer. Although it does not provide the same level of habitat value of the other DCMs considered by the panel, the brine BACM provides effective dust control without any freshwater and, when placed in appropriate locations, serves as a sink for salts flushed from other areas on the lakebed. Examples of hybrid DCMs include managed vegetation combined with either artificial roughness elements or precision wetting. The panel did not attempt to judge the acceptability of those DCMs on environmentally sensitive areas.

Recommendation 1: Additional research on individual and hybrid dust control measures (DCMs) should be conducted to develop new approaches that use less water, maximize other environmental benefits, and ensure that DCMs maintain performance over the long term. Specific research topics to inform future decision making at Owens Lake are provided in Chapter 4 and include the following:

- **Strategies for long-term salinity management in shallow flooding and managed vegetation DCMs, including the capacity to maintain target salinities over time;**
- **Minimum percent coverage needed for alternative vegetation species and mixtures of species as DCMs with the potential to reduce irrigation requirements, and how site-specific conditions on the lakebed impact the performance, durability, and management requirements;**
- **Potential for dynamic precision surface wetting to provide effective control in real-time that reduces water use;**
- **Approaches for enhancing the formation of salt crusts and their long-term stability under a range of conditions;**
- **Performance and feasibility of cobbles and natural and artificial porous roughness as DCMs on the lakebed and their potential to provide additional vegetated habitat;**

- **Potential of hybrid DCMs (such as precision wetting with vegetation) that may lead to further reductions in water use relative to either control measure alone, while increasing habitat value;**
- **Performance and reliability of current and proposed DCMs under future conditions anticipated from climate change, including longer-term changes in climate and more extreme weather events; and**
- **PM_{10} control effectiveness for specific DCMs at various wind speeds.**

Rigorous testing and analysis of new alternative DCMs are necessary to develop approaches that demonstrate dust control effectiveness, require less water, and can meet other objectives. This testing should employ improved methods to quantify PM_{10} emissions, monitor the effectiveness of DCMs, and determine the amount of PM_{10} emission reductions needed to comply with air quality standards. Improved methods are also needed to assess the effects of DCMs on cultural resources.

Several regulatory constraints limit the capacity to test and transition to new or modified DCMs on Owens Lake. For example, regulations require testing of all new alternative BACMs outside of currently regulated dust control areas and limit the area that can be converted to new BACMs. In addition, current regulations might not allow experimentation with hybrid methods. At the same time, strict regulatory time frames for meeting performance standards can limit the use of managed vegetation, which can be a more sustainable DCM in the long term.

IMPROVING METHODS FOR THE EVALUATION OF DUST CONTROL MEASURES

Quantifying PM_{10} Emissions

Development of a dust control strategy to attain PM_{10} air quality standards involves characterizing sources of PM_{10} emissions and the rate at which each source or area emits PM_{10} to the atmosphere. PM_{10} emission rates from individual dust control areas on the Owens Lake bed are estimated using sand flux measurements.[5] DCMs that are highly effective in reducing horizontal sediment transport are also effective in significantly reducing airborne PM_{10} concentrations. However, the relationship between PM_{10} emissions and sand flux is highly variable in space and time, depending on the type and condition of the surface from which PM_{10} is emitted and meteorological conditions. The variability and uncertainty in the measurements and factors used in that relationship can impart considerable uncertainty to the estimated

[5] Sand flux (more generally referred to as horizontal sediment transport) is a measurement of the mass of sand-sized particles per unit time at about 6 inches above a wind-blown surface. Estimating PM_{10} emissions with sand flux measurements involves the use of a semi-empirical relationship that relies upon the horizontal movement of particles, whose sizes include diameters greater than 10 μm.

PM_{10} emissions that are fed into air quality models to demonstrate strategies for complying with air quality standards.

Alternative approaches that use direct measurements of PM_{10} concentrations, made upwind and downwind of dust control areas, can improve the characterization of the level of dust and PM_{10} control provided by DCMs. Recent advances in instrumentation have enabled the development of low-cost and yet accurate sensors of airborne particulate matter. The networking of these sensors with existing monitors could potentially provide operational managers more accurate and precise PM_{10} measurements with enhanced spatial and temporal resolution (see Chapter 2).

The accuracy of air quality models would be enhanced by a more direct quantification of PM_{10} emissions rather than use of horizontal sand flux as a surrogate for PM_{10} emissions. The importance of accurate estimates of a DCM's effectiveness in controlling PM_{10}, and associated uncertainties, increases as airborne PM_{10} concentrations approach the allowable level of the air quality standards. **Estimates of reductions in PM_{10} emissions are associated with a high degree of uncertainty because they have relied primarily on measurements of sand flux.**

Recommendation 2: The District and LADWP should develop and apply additional methods to quantify, with uncertainty estimates, PM_{10} emissions from individual dust control areas, based on direct measurements of airborne PM_{10} concentrations. All devices should be calibrated and tested for representative operation under the field conditions encountered on and around the Owens Lake bed. Testing should include

- **Multiple types of sensors and potential sampling strategies;**
- **Sites on the lakebed with different soil textures and during different seasons; and**
- **Proximity to a meteorological site to obtain observations (e.g., humidity and radiation loading) for characterizing local environmental conditions.**

In addition, there should be a transition period during which the deployment of a network of PM_{10} sensors overlaps with the use of the current monitoring network to determine relationships between the historic sand flux measurements and more directly determined PM_{10} emissions.

Monitoring BACM Effectiveness

When monitoring the effectiveness of deployed BACMs and other DCMs over time, operational managers rely on surrogate metrics (performance criteria) instead of more direct estimates of PM_{10} emissions. These metrics are derived from data collected for this purpose during the BACM testing and approval phases. Examples include the percentage of a control area that must be covered by vegetation or surface water.

The relationships between the performance criteria and PM_{10} control efficiencies are, in some cases, based on analysis with highly variable results. Further, the measurements used to determine compliance with performance criteria are, themselves, uncertain. Although estimates of PM_{10} emissions based on airborne PM_{10} concentrations can also be uncertain, they are more directly related to the desired outcome of the DCMs than are the surrogate metrics currently used in operational evaluations of DCMs.

Tying operational performance of DCMs directly to airborne PM_{10} concentrations could enhance the transparency of air quality management planning, provide flexibility to develop innovative and hybrid control methods, and allow for adaptive responses in areas that experience declines in PM_{10} control efficiency. For example, evaluating performance based on airborne PM_{10} concentrations rather than on the current criterion of 37 percent vegetative cover could demonstrate that less vegetative cover, with the locations and groupings of particular plants tailored to the site, could achieve the expected emission reductions. This in turn would improve management options depending on site conditions and the type of established vegetation. In addition, use of PM_{10} emission estimates may enable hybrid approaches, such as developing vegetative cover on shallow flooding water management areas, and adaptive response, such as adding roughness elements to vegetative cover areas experiencing temporary declines.

One disadvantage of relying on control area–specific estimates of PM_{10} emissions, based on airborne PM_{10} concentration, is the difficulty in assessing compliance under low to moderate wind conditions. Current surrogate metrics for dust control effectiveness can be evaluated under any wind conditions. To serve as a functionally equivalent replacement for surrogate metrics, PM_{10} concentrations and emissions must be characterized as a function of wind speed, so that DCM performance can be evaluated at lower wind conditions when air quality standards are not exceeded.

Operational evaluations of BACMs and other DCMs have relied on surrogate metrics to monitor PM_{10} control efficiency, which introduces a high degree of uncertainty.

Recommendation 3: The District and LADWP should evaluate DCM performance based on PM_{10} emissions from dust control areas, estimated from measurements of airborne PM_{10} concentrations under a variety of wind conditions.

Air Quality Modeling

Air quality models play a central role in determining the amount of PM_{10} emission reductions that will be needed to comply with the NAAQS. The panel recognizes the complexity of the processes that govern PM_{10} emissions from the Owens Lake area and the subsequent transport and dispersion of those emissions. However, the model used to develop the State Implementation Plan[6] to demonstrate attainment of the NAAQS for PM_{10} does

[6] A collection of regulations and documents used by a state, territory, or local air district to reduce air pollution in areas that do not meet the NAAQS.

not use state-of-the-art dispersion formulations. Model performance and hence reliability of future projections of PM_{10} air quality can be improved by paying more attention to the processes that govern emissions and dispersion during high winds, when the highest PM_{10} concentrations occur.

> **Recommendation 4: Air quality models to demonstrate attainment of the National Ambient Air Quality Standards (NAAQS) for PM_{10} should incorporate the current understanding of micrometeorology and dispersion, especially during periods of high winds. Furthermore, the uncertainty associated with modeling those processes should be incorporated into plans to attain the NAAQS.**

UNDERSTANDING AND ENHANCING BENEFITS OF A SYSTEMS APPROACH TO OWENS LAKE DUST CONTROL

LADWP and the District seek new approaches to further reduce airborne PM_{10} concentrations, reduce water use, and meet the requirements of the California State Lands Commission (the main landowner at Owens Lake), the California Department of Fish and Wildlife, and other regulatory agencies, while balancing the concerns of multiple organizations, local tribes, and the general public. Achievement of these goals alone is challenging, and climate change places additional pressures on dust control management at Owens Lake. There is a need to place hybrid or new DCMs in more site-appropriate locations that account for the multifaceted characteristics of the Owens Valley and its environs as an interconnected system.

The complex challenge to meeting the multiple goals related to managing PM_{10} in Owens Lake can be addressed through a landscape-based, systems approach that is flexible and adaptive. Management of DCMs on the lake has occurred in stages as the DCMs have simultaneously evolved, which has led to constraints and strategies that are not always best suited to the lakebed conditions on which they are applied. The need to replace aging infrastructure and to reduce overall water use provides an opportunity to reevaluate the distribution and landscape-scale design of DCMs on the lake. More careful matching of DCMs to local site conditions (e.g., greater use of managed vegetation on sandy areas that are easily leached by shallow flooding) could achieve long-term dust control with lower water use, lower maintenance costs, and improved salinity management. Landscape-based planning also allows for consideration of control-area size and adjacency issues that could result in reduced water and energy use and improved long-term control. For example, placing brine ponds downgradient from managed vegetation enables reuse of drainage waters and reduction in pumping costs. Keeping shallow flooding away from managed vegetation (where groundwater salinity is a critical consideration) also reduces pumping requirements. **However, the requirement that restricts application of new DCMs to no more than 3 square miles limits the timely transition to more integrated lake-wide dust management practices.**

Ultimately, improvements in dust control to reduce PM_{10} concentrations with lower water use, while protecting environmental resources, will result in tradeoffs that have yet to be fully understood. Such tradeoffs are best evaluated and measured in a systematic way to identify the best selection and application of DCMs and to understand how alteration of one DCM can affect system-level performance. Significant reductions in water use will decrease the areal extent of shallow saline water, which supports a robust food web (e.g., brine flies and shrimp) and provides critical habitat for migrating and breeding shorebirds and waterfowl. Irrigated managed vegetation areas support habitats similar to the alkali meadows that are valuable habitat and were once common in the Owens Valley but are now regionally rare. Some level of water use is necessary to sustain all habitats on the lakebed, although different habitats require different amounts. Current habitat modeling focuses on habitat for multiple bird guilds, without a priority for habitats that are unique along avian flyway corridors or regionally rare. Needed is additional information to support the development of a long-term management plan that aims for integrated, spatially, biologically, and culturally appropriate PM_{10} emissions control, while accounting for water use, habitat, and preservation of cultural resources (see Chapter 5).

Recommendation 5: To support the development of a landscape-based, systems approach with multiple goals, dust control configurations should be assessed within a lake-wide context, considering long-term management of air quality, surface and groundwater, and salinity; protection of cultural resources; and the regional significance of habitat types and other ecosystems services in the Owens Valley.

FUTURE OLSAP CONSIDERATIONS

As indicated in the 2014 Stipulated Judgment, this report is the first in an expected series of reports by OLSAP. Through continued engagement, OLSAP will provide ongoing assessments and scientific advice on the challenges associated with developing sustainable approaches to reduce dust in the Owens Valley. Through its upcoming activities, the panel could provide valuable advice on implementing the recommendations in this report, especially those regarding the use of PM_{10} concentration measurements to quantify emissions from control areas and the application of landscape-based, systems approaches to assess dust control configurations at Owens Lake.

1

Introduction

OWENS LAKE: A SOURCE OF DUST EMISSIONS

Owens Lake is located in eastern-central California at the southern end of the Owens Valley. During the late 1800s, prior to water diversions, Owens Lake was a closed-basin saline lake covering about 100 square miles, with a maximum depth of approximately 50 feet. Beginning in 1913, water was diverted from the Owens River (the primary inflow to the lake) into the Los Angeles Aqueduct for the city of Los Angeles. The diversion caused large portions of the Owens Lake bed to dry out, shrinking the lake to less than one-third its former area and leaving a shallow hypersaline brine dominated by salts of sodium carbonate and sodium sulfate (Mihevc et al., 1997). Although many salt flats and lakes (e.g., Bonneville Salt Flats, Salar de Uuyni) have hard and stable salt crusts dominated by sodium chloride, the sodium carbonate and sodium sulfate dominated mineral composition of Owens Lake brines resulted in easily erodible dry saline silty soils and fragile salt crusts. This phenomenon is also observed at other saline lakes undergoing desiccation such as the Salton Sea (California), Lake Urmia (Iran), and the Aral Sea (Kazakhstan and Uzbekistan). The resulting dry areas of Owens Lake bed contained several areas with sandy sediments, especially near the Owens River delta. These sandy sediments can abrade dust from weak crusts and soil aggregates during wind events, compounding the erodibility of the lakebed. The dry lakebed produced large amounts of airborne dust under high wind conditions, resulting in the highest concentrations of airborne particulate matter smaller than 10 micrometers (μm; PM_{10}) in the country (CARB, 2016) (see Figure 1-1).

Legal and Regulatory History of Air Pollution Control

Airborne particulate matter is one of six criteria pollutants regulated under the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS). In addition, the state of California sets ambient air quality standards (CAAQS).[1]

[1] Attainment of the NAAQS has precedence over attainment of the CAAQS due to penalties for failure to meet NAAQS deadlines. California law does not require that CAAQS be met by specified dates. Instead, the law requires incremental progress toward attainment (CARB, 2020).

FIGURE 1-1 Dust storm at Owens Lake in 2010.
SOURCE: Brian Russell, GBUAPCD in Kiddoo, 2019.

Two size-categories of airborne particulate matter are currently regulated by EPA and the state of California: PM_{10} and $PM_{2.5}$ (particles 10 μm and 2.5 μm or smaller in aerodynamic diameter, respectively) (CARB, 2019; EPA, 2016). EPA's Integrated Science Assessment for Particulate Matter evaluates and synthesizes research findings on the public health effects and other effects (e.g., reduced atmospheric visibility) associated with airborne PM_{10} and $PM_{2.5}$ (EPA, 2019a). As discussed below, this report is focused on PM_{10}. The NAAQS for PM_{10} is 150 $\mu g/m^3$, with an averaging time of 24 hours. The CAAQS for PM_{10} is 50 $\mu g/m^3$, with an averaging time of 24 hours and 20 $\mu g/m^3$, with an averaging time of 1 year.[2] States have the primary responsibility to prepare a State Implementation Plan (SIP) for achieving and maintaining the NAAQS within each air quality control region within the state. The SIP establishes emission limits and other control measures that are designed to achieve NAAQS attainment in nonattainment regions.

In 1987, EPA designated the southern Owens Valley (known as the Owens Valley Planning Area or OVPA), where Owens Lake is situated, as being in nonattainment of the 24-hour-average PM_{10} NAAQS (see Figure 1-2). The area also has been designated by the state of California as being in nonattainment of the corresponding state standards. The California Air Resources Board delegated responsibility for developing and enforcing

[2] Air quality data statistics for $PM_{10,}$ $PM_{2.5,}$ and other pollutants throughout the state of California are available at: https://www.arb.ca.gov/adam/trends/trends1.php (accessed January 28, 2020).

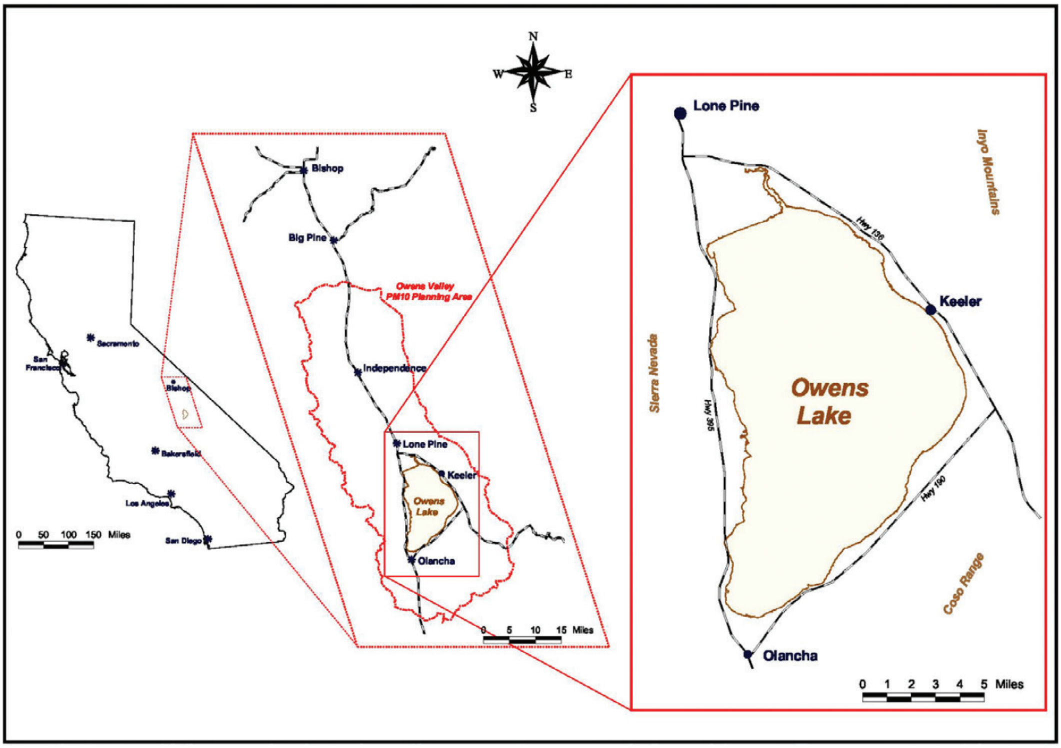

FIGURE 1-2 Location of Owens Lake within the Owens Valley Planning Area. The figure delineates the regulatory shoreline of Owens Lake, which has been set at an elevation of 3,600 ft.
SOURCE: GBUAPCD, 2016a.

the SIP to the Great Basin Unified Air Pollution Control District (hereafter, the District) for areas in the District's jurisdiction. The District determined that the Owens Lake bed should be controlled as an anthropogenic source of PM_{10} because the Los Angeles Aqueduct diverted water sources that historically supplied the lake. The Los Angeles Department of Water and Power (LADWP) was deemed legally responsible for controlling particulate emissions from the dry lakebed.[3] The Owens Lake bed is defined in regulations as the area below 3,600 feet above mean sea level. The current ordinary high water elevation is about 3,554 feet (GBUAPCD, 2016a).

[3] Legal requirements and enforcement mechanisms include District Governing Board Order #160413-01 (Requiring the City of Los Angeles to Undertake Measures to Control PM_{10} Emissions from the Dried Bed of Owens Lake), District Rule 433 (Control of Particulate Emissions At Owens Lake), California Health and Safety Code 42316 (District may require the City of Los Angeles to undertake reasonable measure to mitigate the air quality impacts of its activities in the production, diversion, storage, or conveyance of water. . .).

Dust Management at Owens Lake

In the 1998 SIP for the OVPA (GBUAPCD, 1998), the District outlined plans for implementing dust control measures (DCMs) to reduce PM_{10} emissions on 16.5 square miles of the lakebed, and LADWP began construction in 2000 (see Figure 1-3). The District subsequently developed SIPs in 2003, 2008, and 2016 to require DCMs over larger areas of the lakebed in order to attain the NAAQS for PM_{10} (GBUAPCD, 2003, 2008, 2016a).

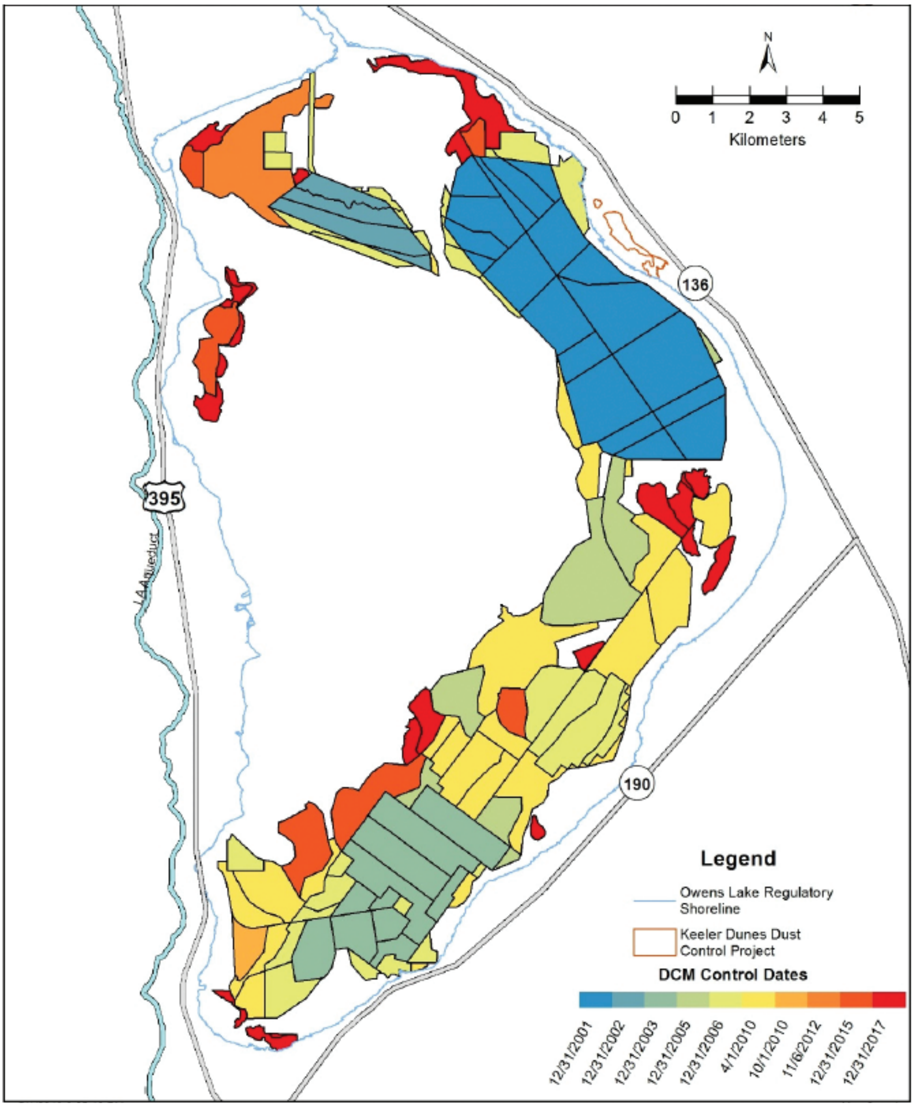

FIGURE 1-3 Timeline of dust control implementation at Owens Lake.
SOURCE: Kiddoo, 2019.

As of April 2019, 48.9 square miles of lakebed (below the regulatory shoreline elevation of 3,600 feet and at or above Owens Lake's ordinary high water elevation of 3,553.55 feet) had been ordered for PM_{10} control.[4]

DCMs can range widely in the type of control and their effectiveness. For a serious nonattainment area with fugitive dust sources, Best Available Control Measures (BACMs) are required and defined by the Clean Air Act. In the context of the Owens Valley, BACMs are defined as "best available control measures designed to reduce PM_{10} emissions to Control Efficiency (CE) levels . . . through compliance with [specific] performance standards." Control efficiency levels are established as 99 percent reduction in PM_{10} emissions for the regulated areas on the lakebed.[5] As of April 2019, BACMs were used across 46.6 square miles of the lakebed to control PM_{10} emissions (see Figure 1-4).

Three categories of BACMs have been approved for use on the lake: shallow flooding, managed vegetation, and gravel (see Box 1-1). These BACMs were determined from a research and testing program at Owens Lake starting in 1980 and overseen by the District. These BACMs were designated by the District in the 1994 and 1998 SIPs and were approved by EPA in 2000. Subsequently, several modifications to the BACMs have been adopted; for example, approved modifications to the Shallow Flooding BACM are Tillage with Shallow Flooding Backup, Brine with Shallow Flooding Backup, and Dynamic Water Management. Table 1-1 summarizes the areas controlled with each BACM as of April 2019. The Shallow Flooding BACM is, by far, the most widespread DCM, by surface area, applied at Owens Lake (see also Figure 1-4). See Chapter 4 for additional discussion of these BACMs and other DCMs.

In specific areas of the lakebed, beginning in 2008, the District permitted the use of minimum dust control efficiency BACMs to reduce water use or address environmental concerns. In these areas, required control efficiency may be less than 99 percent, if approved by the District. The specific control efficiency targets for each individual dust control area are set based on the levels of control necessary to prevent exceedances of the NAAQS, as determined by air quality modeling (GBUAPCB, 2008, 2016a). As of 2019, 0.9 square miles are controlled with minimum dust control efficiency BACMs (see Table 1-1). An example is the use of sand fences on approximately 0.4 square miles toward the southern end of the lakebed. Scattered among the areas that have been ordered for dust control are several environmentally sensitive areas (1.2 square miles total) that remain uncontrolled; such areas have been deferred by the District because of the presence of eligible cultural resources.

Although most OVPA PM_{10} control efforts have focused on the ordered dust control areas on the Owens Lake bed, the District has implemented off-lake dust control measures

[4] Although the regulatory text in Rule 433, Board Order #160413-01, and GBUAPCD (2018) state 48.6 square miles of dust control, the area resulting from the coordinates listed and ordered in the same documents totals 48.9 square miles. Thus the District considers the total ordered area to be 48.9 square miles (Logan, 2020).

[5] District Rule 433, Control of Particulate Emissions at Owens Lake, adopted 04/13/2016. See https://ww3.arb.ca.gov/drdb/gbu/curhtml/r433.pdf (accessed January 28, 2020).

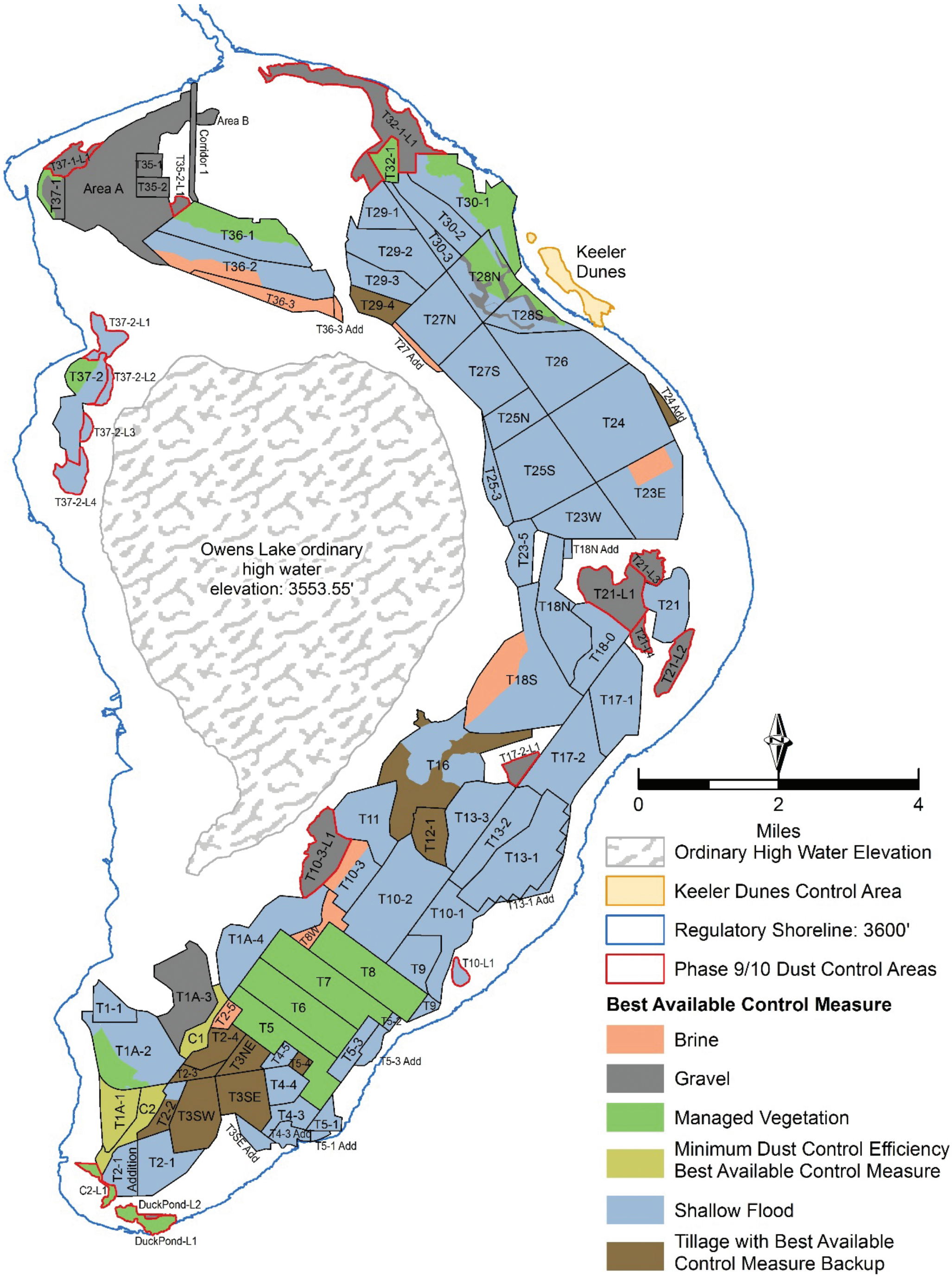

FIGURE 1-4 Map of Owens Lake showing the regulatory shoreline, brine pool, and ordered dust control areas.
SOURCE: GBUAPCD, 2016a.

Box 1-1
Current Best Available Control Measures (BACMs) and Approved BACM Modifications

The following three categories of BACMs been approved for use on the Owens Lake bed:

- Shallow Flooding:
  - *Shallow Flooding:* Use of standing water or surface-saturated soil to eliminate dust emissions and trap wind-blown sand that enters the ponded area.
  - *Dynamic Water Management:* An operational modification of shallow flooding that allows for later start dates and/or earlier end dates to reduce water use in areas that have had historically low PM_{10} emissions.
  - *Brine with Shallow Flooding Backup:* Application of brine and/or development of a thick salt crust to stabilize the surface. Shallow flooding is required when the surface condition deteriorates to a potentially emissive state.
  - *Tillage with Shallow Flooding Backup:* Use of mechanical methods to create a series of plowed ridges and furrows, generally oriented perpendicular to the predominant winds to enhance surface roughness and reduce near-surface winds. Shallow flooding is required as a backup when the performance criteria for dust control are not met.
- *Managed Vegetation:* Planting of locally adapted, native vegetation to cover and protect the surface from wind, decrease wind energy at the soil surface, and trap saltating particles.
- *Gravel:* A zero-water control measure that involves the placement of a layer of gravel on the surface or on top of a permanent permeable geotextile fabric.

TABLE 1-1 Dust Control Status as of April 2019

BACM		Square Miles
Gravel		5.4
Managed Vegetation		5.4
Shallow Flood	Shallow Flooding (including Dynamic Water Management areas[a])	29.7
	Brine with Shallow Flooding Backup	3.8
	Tillage with Shallow Flooding Backup	2.7
Minimum Dust Control Efficiency Areas		0.9
Total area ordered and controlled as of April 2019		**47.8**
Ordered but not controlled[b]		**1.2**

[a] In the 2018/2019 water year, 10.5 square miles of this area was operated for dynamic water management.
[b] Includes environmentally sensitive areas, such as areas that have been deferred because of the presence of eligible cultural resources meeting requirements per the District order.
SOURCE: Logan, 2019a; Valenzuela, 2019a.

(beyond the regulatory shoreline) at the Keeler Dunes.[6] The project uses straw bales and planted shrubs as dust control measures (see Chapter 4 for more details).

As of 2019, LADWP estimates that $2.1 billion has been spent on managing dust at Owens Lake. That estimated cost consists of capital costs to construct large dust control infrastructure on 47.8 square miles (55 percent), operating and maintenance costs (18 percent), water use (21 percent), and regulatory fees (6 percent) (Valenzuela, 2019a).[7]

Many of the BACMs defined in the SIPs and implemented in the ordered dust control areas involve the use of water. The quantity of freshwater used for current dust control activity is estimated to be approximately 60,000 acre-ft/year, with year-to-year variability from approximately 45,000 to 70,000 acre-ft/year (Agahi, 2019). Since 2007, annual water use for dust control represents roughly 30 percent of available LADWP freshwater supplies at Owens Lake,[8] with an annual range of 17 to 51 percent. Long-term water availability to southern California is projected to decline with climate change and changing water allocations from the Colorado River under newly implemented drought contingency plans (P.L.116-14). Modifications of BACM requirements to conserve water use saved an average of about 22,000 acre-ft/year from 2014 through 2016 compared to the average water use from 2011 through 2013 (GBUAPCD, 2018). More-detailed analyses of the water use associated with various DCMs are provided in Chapter 3.

CHALLENGES

The tension between water use and dust control in the OVPA represents a serious challenge to meeting the NAAQS for PM_{10}. LADWP and the District have agreed through a Stipulated Judgment to move toward less reliance on shallow flooding for dust control and to investigate new and refined DCMs to reduce overall water demand.[9] The Judgment states, "New dust control measures should be waterless where feasible. Where not feasible, new dust control measures should be water neutral by offsetting any new or increased water use with water savings elsewhere on the lakebed." New or refined waterless measures could include engineered roughness, soil binders, and improved tillage strategies. In addition, vegetation, such as playa scrub species, could provide dust control as well as habitat, positive aesthetics, and protection of cultural resources, with minimal long-term irrigation needs, particularly around the lake edges.

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[6] Under the 2013 Stipulated Order of Abatement, LADWP contributed $10 million as a "public benefit contribution" to the District for PM_{10} control at the Keeler Dunes. In return, LADWP would be released "from any and all liability for dust emissions, regardless of origin, from the Keeler Dunes and other dune areas in the vicinity of Owens Lake" (GBUAPCB, 2016a).

[7] See GBUAPCD (2016a, p. 58) for additional information on costs.

[8] Available water is assumed to be the sum of LADWP exports in the Los Angeles Aqueduct and Owens Lake freshwater use for dust control. See Chapter 3.

[9] Stipulated Judgment in the matter of the City of Los Angeles v. the California Air Resources Board et al. Superior Court of the State of California, County of Sacramento. Case No. 34-2013-80001451-CU-WM-GDS. Approved by the court on December 30, 2014. See https://gbuapcd.org/Docs/District/AirQualityPlans/SIP_Archive/2014_Stipulated_Judgment_20141230.pdf (accessed January 28, 2020).

Implementation of DCMs is also challenged by the needs to maintain ecological habitat and mitigate impacts to cultural resources and other environmental resources. Currently, approximately 277 acres are excluded from on-site DCMs because they have been identified as Eligible Cultural Resources (ECRs) (GBUAPCD, 2016a, p. 49). If adjacent DCMs are insufficient to control PM_{10} emissions from these areas, dust control may be ordered for any ECR area determined to have caused or contributed to an exceedance of air quality standards. Representatives of Native American tribes in Owens Valley have voiced concerns about the land disturbance (which can destroy cultural artifacts and disrupt the natural land forms that are culturally important), road building (which not only involves land disturbance but also increases access to looters), and unnatural aesthetics of some of the managed areas at Owens Lake, as well as about protection of historical and archeological resources (Bancroft, 2013).

The large expanses of shallow flooding combined with natural wetlands provide attractive habitat for migratory and nesting birds. The area attracts thousands of sandpipers, ducks, and other shorebirds, and it provides breeding habitat for the Snowy Plover, Yellow-headed Blackbird, and Long-billed Curlew.[10] Owens Lake has been designated an "Important Bird Area" by the National Audubon Society, and efforts to reduce water use in dust mitigation will likely impact existing habitat. The habitats of Owens Lake are discussed in detail in Chapter 3.

Other challenges that affect dust management decisions at Owens Lake include the long-term durability and reliability of the DCMs, economic costs, and energy use. Factors that affect the durability of DCMs include the corrosive nature of the soils, flooding from snow melt, and the uncertain long-term availability of water due to climate change.

STATEMENT OF TASK

To help address these ongoing challenges, LADWP and the District agreed under the 2014 Stipulated Judgment to contract with the National Academies of Sciences, Engineering, and Medicine (NASEM) to establish the Owens Lake Scientific Advisory Panel (OLSAP). According to the 2014 Stipulated Judgment,

> *[t]he purpose of the OLSAP is to evaluate, assess, and provide ongoing advice on the reduction of airborne dust in the Owens Valley. The Panel will review scientific and technical issues related to the research, development and implementation of waterless and low water use BACM, and other approaches to reduce dust in the Owens Valley. The Parties intend for the Panel to foster communication and understanding on the scientific and technical approaches and become a vehicle for increased cooperation and collaboration between the District and the City in balancing the requirement to meet air quality standards and conserve water (p. 13).*

[10] See https://www.audubon.org/important-bird-areas/owens-lake (accessed January 28, 2020).

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

As indicated in the 2014 Stipulated Judgment, the panel's first task is to

> *[e]valuate the effectiveness of alternative dust control methodologies for their degree of PM_{10} reduction at the Owens Lakebed and to reduce use of water in controlling dust emissions from the dried lakebed. The evaluation should consider associated energy, environmental and economic impacts, and assess the durability and reliability of such control methods (p. 14).*

In response to that request, NASEM established the OLSAP to carry out the first task. (See Appendix A for biographical sketches of the panel members.) In interpreting its charge and its overarching purpose, the panel considered the term *effectiveness* to mean the level of PM_{10} emission control (e.g., 99 percent) achieved by a DCM. That definition is consistent with the meaning of control effectiveness (or control efficiency) used in the SIP (GBUAPCD, 2016a). The panel considered the reliability of the DCMs under current and potential future extreme weather events under a changing climate.

The panel also determined that its charge included consideration of both lakebed (on-lake) and off-lake sources of PM_{10} that are adjacent to lakebed dust control areas. This interpretation is based on the recognition that PM_{10} reduction at the Owens Lake bed will result from a variety of sources on the lakebed and that sediment mobilized from the lakebed may have been transported to off-lake areas that are now PM_{10} sources. In addition, the District has concluded that PM_{10} emissions from off-lake areas continue to pose the largest challenge for attainment of PM_{10} air quality standards within the OVPA. According to monitoring and modeling analyses conducted by the District, emissions from off-lake sources more than 2 kilometers (1.2 miles) from the lakebed do not influence attainment (GBUAPCD, 2016a). Therefore, although the panel primarily focused on lakebed sources of PM_{10}, it also evaluated DCMs that could be effective for nearby sources. This approach is consistent with the overall purpose of OLSAP to examine airborne dust in the Owens Valley. However, for this task the panel's evaluation of DCMs did not consider application to potential dust sources that are distant from the Owens Lake bed.

The panel's interpretation of its charge was informed by the definition of *environment* found in The California Environmental Quality Act (CEQA):

> *"Environment" means the physical conditions which exist within the area which will be affected by a proposed project including land, air, water, minerals, flora, fauna, ambient noise, and objects of historical or aesthetic significance. The area involved shall be the area in which significant effects would occur either directly or indirectly as a result of the project. The "environment" includes both natural and man-made conditions.*[11]

[11] Title 14. California Code of Regulations, Chapter 3. Guidelines for Implementation of the California Environmental Quality Act, Section 15360. Environment. Available at http://www.resources.ca.gov/ceqa/guidelines/art20.html (accessed January 28, 2020).

Therefore, the panel interpreted its charge to include evaluation of the potential effects of DCMs on the cultural resources of Native American tribes in the Owens Valley. Based on priorities expressed in public statements and information available in the public record, the committee focused its assessment of the effects of DCM alternatives on cultural resources on the likelihood of land disturbance, which could harm archaeological resources, and effects on habitat and natural aesthetics, which are also valued cultural resources.

In choosing the types of DCMs to evaluate, the panel combined BACMs and other DCMs under the general term of *alternative dust control methodologies*. It did not evaluate the alternative dust mitigation strategy of restoring the lake by modifying the amount of water diverted to Los Angeles and allowing the lake to refill and reach a steady state. Evaluation of that strategy falls outside the committee's charge, which is focused on DCMs that reduce the use of water to control dust emissions for the dried lakebed, and would require substantial effort to gather and analyze the necessary data.

This report reflects the consensus of the panel members, based on briefings from agencies, organizations, and individuals received during the public sessions of the May and July 2019 meetings, three Web conferences in July and August 2019, and three field-trip sessions at Owens Lake in July 2019, including one field-trip session focused on Native American perspectives and concerns (see Appendix B); documents provided to the panel; relevant scientific literature; and the knowledge and experience of the panel members in their fields of expertise.

ORGANIZATION OF THE REPORT

Chapter 2 discusses the wind erosion processes that lead to fugitive dust emissions, air monitoring systems in use at Owens Lake, monitoring data trends, and air quality modeling. Chapter 3 discusses key contextual factors for evaluating DCMs, including hydrology and water resources; areas on the Owens Lake bed that are culturally significant to Native American tribes; habitats; and mineral resources. Chapter 4 assesses 15 DCMs that represent a range of mitigation approaches that are either currently applied at Owens Lake or at various stages of development. Chapter 5 outlines an integrated systems approach to dust control for meeting current and future challenges.

2

Air Quality

This chapter discusses wind erosion processes at Owens Lake that contribute to airborne particulate matter in the Owens Valley, air quality monitoring at Owens Lake, approaches for estimating PM_{10} emissions, and air quality modeling conducted as a part of developing a State Implementation Plan (SIP) to attain National Ambient Air Quality Standards (NAAQS) for particulate matter with an aerodynamic diameter of 10 micrometers or less (µm; PM_{10}). Those topics are important for understanding the impact of dust control measures (DCMs) on airborne PM_{10} concentrations and making progress toward attainment of the NAAQS.

DUST GENERATION VIA WIND EROSION

Wind erosion results when the atmosphere in motion (wind) interacts with the granular media (sediments) on Earth's surface. It affects more than 500 million hectares of land worldwide and results in 2 billion tons of dust emissions annually (Shao et al., 2011). Fugitive dust is often the most visible evidence of wind erosion and has detrimental impacts on commerce, air quality, and human health.

Earth's surface exerts a drag on wind flow that results in shear forces capable of lifting and transporting sediment particles on the surface once the threshold wind velocity for that surface has been exceeded. Natural turbulence in the atmospheric boundary layer at the surface, caused by physical obstructions and convective overturn, results in wind gusts and lulls that often vary significantly from mean wind speeds. As the force of wind varies with the square of the wind speed, the shear forces near the surface will also vary, to a greater extent, along with incident wind speed. In addition, for mean 2-minute wind speeds in excess of 12 m/s (26.8 mph), the instantaneous wind speed in the 1 cm layer above the surface will exceed the 2-minute mean wind speed at least 5 percent of the time, resulting in very high shear stresses on surface particles (Van Pelt et al., 2006). For this reason, just a few extreme wind events often result in the predominance of soil redistribution and dust emissions at a given location. For instance, at a location in the Southern High Plains of North America, detailed wind erosion data were taken for 172 wind events during a 9-year period. Analysis of those data revealed that a single event was responsible for 8 percent of total soil loss, the most intense 10 percent of storms (17) accounted for 50 percent of the total soil loss, and the most intense 50 percent of storms (86) resulted in 93 percent of the total soil loss measured during the time period (Van Pelt et al., 2006).

Wind-entrained particles move in three phases: creep, saltation, and suspension (Bagnold, 1941) (see Figure 2-1). In general, particles and aggregates larger than 840 μm in diameter are considered unerodable, but such particles and aggregates may be forced over the surface in very high velocity wind events. These larger particles and aggregates are in creep mode, because they do not leave the surface to be accelerated by the wind.

Saltation and suspension processes cause particles and aggregates to become airborne. For the saltation process, particles are lifted by shear forces into the air, accelerated by the wind, and return by gravity to the surface with a velocity-augmented impact energy. When saltating particles strike the surface, they may bounce, eject more particles and thus increase saltation, or abrade fine suspension-sized particles from crusted surfaces or aggregates (Shao, 2001).

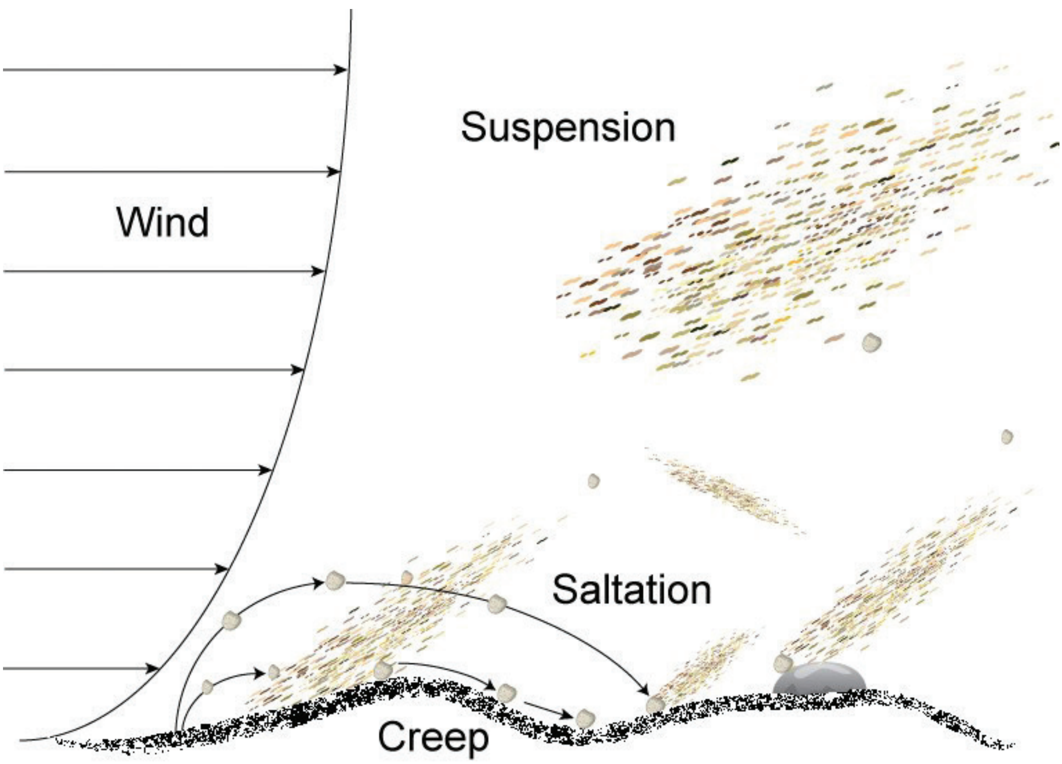


FIGURE 2-1 Modes of wind-induced particle movements.
NOTES: The arrows on the left represent relative wind speeds and show the logarithmic decrease of velocity near the surface. Larger particles and aggregates move in creep mode, fine– and medium sand–sized particles move in saltation mode, and smaller particles enter true suspension and are transported away from the source by the wind. Particles are not drawn to scale.
SOURCE: Zobeck and Van Pelt, 2011.

Suspension occurs when smaller particles are directly entrained (emitted) into the air. Once airborne, the particles can be transported over long distances.

The absolute particle diameter separating saltation and suspension is determined by the velocity of the wind, but in general, the separation has been proposed to be in the range of 100 µm (Hagen et al., 2010) or smaller but almost always in the diameter range for very fine sand, with smaller particles becoming airborne via suspension. Particles or aggregates larger than 100 µm in diameter (primarily fine and medium sand) move via saltation. Therefore, sediments can contribute to airborne PM_{10} concentration through direct suspension of loose PM_{10} in surface sediments created by weathering and mechanical forces, abrasion of immobile aggregates and crusts by saltation impacts, and breakage of mobile saltation and creep-sized aggregates and particles into suspension size.

Field studies have shown that much of the coarser fraction of particles in the suspension mode are deposited on the surface within a few hundred meters of their source (Hagen et al., 2007). The finer portions, including PM_{10}, may be lofted to great altitudes and transported hundreds or thousands of kilometers before returning to Earth's surface (Cahill et al., 1994; Shao et al., 2011).

EFFECTS OF SEASONALITY ON DUST EMISSIONS AT OWENS LAKE

The climate of the Owens Valley is similar to many arid and semi-arid regions of the world, with summer temperatures often exceeding 100°F and winter temperatures commonly below freezing at night. Winds in the Owens Lake vicinity are generally from the north or south, although strong westerly winds can occur. However wind direction and wind speed are highly variable. Winds can be generated by synoptic storms, as well as local summer convection storms. Duell (1990) reports wind speeds in excess of 30 mph are not uncommon. Danskin (1998) reports that elevated winds can occur at any time of the year but are often associated with winter and spring storm systems.

The contrast between winter and summer temperatures is, in part, responsible for the development of emissive salt crust surfaces at Owens Lake. During warm summer months, the surface salts are dominated by Trona and Burkeite. However, during colder months, these salts transition to their hydrated versions including Thermonatrite, Natron, and Glauber's salt (Scheidlinger, 2008a), which are light and easily erodible if allowed to dry. Therefore, as a result of both wind conditions and geochemistry, the colder months of the year are the most prone to dust emission from the lakebed. Dust control strategies such as shallow flooding take advantage of this seasonality of potential dust production, and are typically only deployed from October 16 to June 30.

AIR QUALITY MONITORING REQUIREMENTS

Title 40 of the Code of Federal Regulations (CFR), Part 58, Appendix D requires that air quality monitoring be conducted to inform the public, support compliance with the air quality standards and emissions strategy development, and support research studies. An area that may be (or has been determined to be) in nonattainment with applicable NAAQS is required to conduct monitoring. In January 1987, the U.S. Environmental Protection Agency (EPA) set a new PM_{10} standard at 150 μg/m^3, with an averaging time of 24 hours. An exceedance with respect to the NAAQS is defined in 40 CFR 50.1(l) as "one occurrence of a measured or modeled concentration that exceeds the specified concentration level of such standard for the averaging period specified by the standard." The level of the PM_{10} standard may not be exceeded more than once per year on average over 3 years. In addition, the state of California has set a more-stringent air quality PM_{10} standard at 50 μg/m^3 (see Chapter 1).

In 1987, EPA determined that the southern Owens Valley area (now referred to as the Owens Valley Planning Area [OVPA]) was in violation of the new NAAQS for PM_{10}. The District monitors PM_{10} at Keeler, Olancha, Lone Pine, Dirty Socks, Lizard Tail, Shell Cut, Stanley, Mill, and North Beach, both to better characterize the problem, as well as to lay a foundation for developing effective emissions control strategies (see Figure 2-2). These PM_{10} monitoring sites are all located in areas surrounding the lakebed, both very near the regulatory shoreline and elsewhere in the Owens Valley (e.g., Lone Pine, approximately 3 miles away). On-lake special purpose PM_{10} monitors are used to determine compliance with required performance criteria. Monitoring is also used to evaluate compliance with the California air quality standards, which are more focused on locations that present exposures to populations.

The compliance monitoring for the NAAQS for PM_{10} is conducted using Tapered Element Oscillating Microbalance (TEOM) instruments. TEOMs are Federal Equivalent Method (FEM)[1] monitors that provide semi-continuous data. Typically reported for compliance purposes on a 24-hour average basis, they can provide data at much shorter time resolutions (minute-level), although shorter averaging times lead to increased uncertainty. At Owens Lake, hourly TEOM PM_{10} data are reported to EPA. In addition, the Keeler monitoring site has two PM_{10} Partisol samplers (filter-based, Federal Reference Method [FRM] for sampling the ambient air and analyzing for an air pollutant), as well as a TEOM and Partisols for $PM_{2.5}$ (particles 2.5 μm or smaller in aerodynamic diameter).[2] Filter-based monitoring is typically conducted for 24-hour periods (midnight to midnight), but not necessarily daily. One advantage of filter-based monitoring is that the filters can also be used to conduct speciation (chemical) analysis, and hence provide critical information for source identification, although this use has not been a focus to date. A main disadvantage of using 24-hour filter sampling is that dust events are typically short term (<24 hours), so a 24-hour sample would not fully capture the magnitude of the event, or the relationship to the direction or speed of the wind.

Sensors located next to the PM_{10} monitors measure wind speed and direction; the resulting information could be used to estimate the direction of the PM_{10} sources relative to the

[1] A method for measuring the concentration of an air pollutant in the ambient air that has been designated as an equivalent method in accordance with 40 CFR 53.

[2] Air quality data statistics for PM_{10}, $PM_{2.5}$, and other pollutants throughout the state of California are available at: https://www.arb.ca.gov/adam/trends/trends1.php (accessed January 28, 2020).

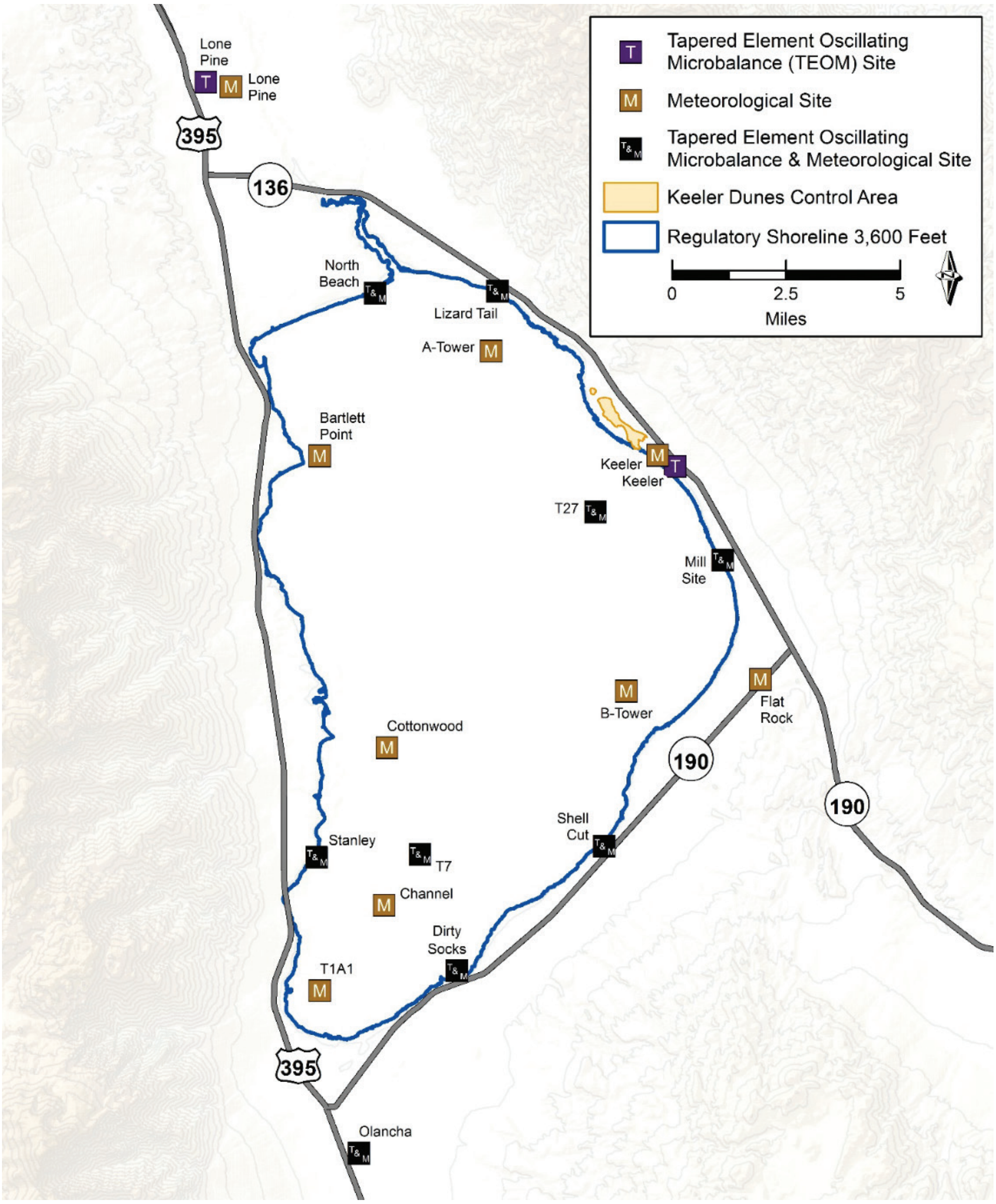
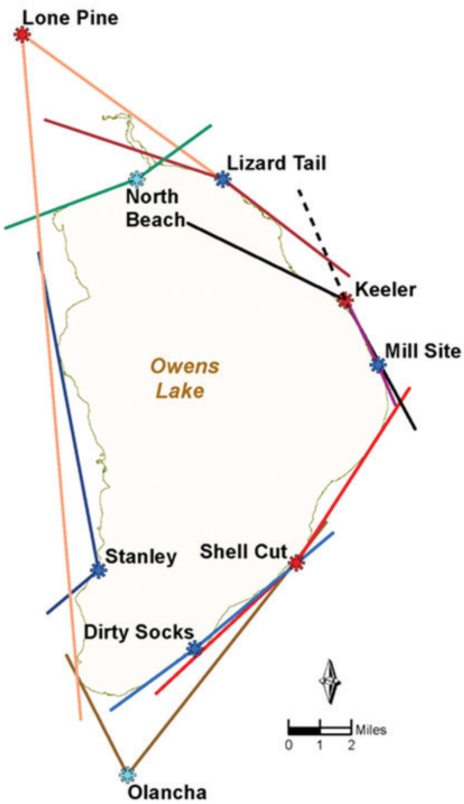


FIGURE 2-2 Locations of PM_{10} monitors and meteorological stations around Owens Lake.
SOURCE: GBUAPCD, 2016a.



Wind Directions to Determine Lakebed-caused Monitored Exceedances

PM_{10} Monitor Site	From-the-Lake Wind Dir. (Deg.)	Non-lake Wind Dir. (Deg.)
Lone Pine	$126 \le WD \le 176$	$WD < 126$ or $WD > 176$
Keeler	$151 \le WD \le 296$	$WD < 151$ or $WD > 296$
Flat Rock	$224 \le WD \le 345$	$WD < 224$ or $WD > 345$
Shell Cut	$WD \ge 227$ or $WD \le 33$	$33 < WD < 227$
Dirty Socks	$WD \ge 234$ or $WD \le 50$	$50 < WD < 234$
Olancha	$WD \ge 333$ or $WD \le 39$	$39 < WD < 333$
Bill Stanley	$WD \ge 349$ or $WD \le 230$	$WD < 349$ or $WD > 230$
Lizard Tail	$128 \le WD \le 288$	$WD < 128$ or $WD > 288$
North Beach	$55 \le WD \le 250$	$WD < 55$ or $WD > 250$
Mill Site	$157 \le WD \le 333$	$WD < 157$ or $WD > 333$

FIGURE 2-3 Wind direction assessments used to characterize on-lake and off-lake source regions.
NOTE: Wind directions from the lake toward a PM_{10} monitor are illustrated by two straight lines extending from a PM_{10} monitor site to the points on the regulatory shoreline that maximize the angle between the two straight lines in the direction of the lakebed. Wind directions in the table are degrees from the north.
SOURCE: Logan, 2019a.

monitor, as well as provide information for quantifying PM_{10} emissions. Figure 2-3 illustrates an assessment of wind directions at PM_{10} monitoring sites to determine whether the origin of the observed PM_{10} is predominantly from on-lake or off-lake sources. Additional meteorological sites support application of the Owens Lake Dust Identification Model ("Dust ID Model"), which is a tool for identifying dust control areas on the lakebed (GBUAPCD, 2016a).

In addition to the PM_{10} monitors, the Great Basin Unified Air Pollution Control District in California (District) monitors $PM_{2.5}$ at the Keeler site (using $PM_{2.5}$ TEOM and $PM_{2.5}$ Partisol monitors). Additional PM monitoring is conducted at Federal Class I IMPROVE sites in the area (near Bishop, California), focusing on particles that contribute to haze formation and thereby reduce atmospheric visibility. Those sites include monitors that allow for speciation of $PM_{2.5}$ components, which can help inform air quality planners on the transport of PM and, to a degree, relative strengths of emission sources.

TRENDS IN AIR QUALITY MONITORING DATA

Extensive data collection has occurred at various sites in the lake areas, with the key objective to monitor exceedances of NAAQS PM_{10} levels. Monitoring data show the number of exceedances has steadily decreased since 2000 (see Table 2-1) because of implementation

TABLE 2-1 Exceedances of the PM_{10} NAAQS at Monitors around Owens Lake from 2000 to 2019

Year	Area Covered by DCMs (% of lakebed)	Average Exceedance ($\mu g/m^3$)	Maximum Exceedance ($\mu g/m^3$)	Exceedance Day Count[a]
2000	0	1,087	10,840	37
2001	10.85	1,413	20,750	46
2002	12.53	800	7,915	49
2003	17.71	1,115	16,619	37
2004	17.71	808	5,225	35
2005	21.41	627	3,988	28
2006	27.37	940	8,299	33
2007	27.37	272	727	14
2008	27.37	319	814	15
2009	27.37	339	1,506	19
2010	36.63	603	4,570	29
2011	36.63	641	13,380	24
2012	38.45	495	3,916	23
2013	38.45	283	529	13
2014	38.45	360	1,015	10
2015	40.75	337	1,487	14
2016	40.75	249	530	16
2017	42.75	411	2,164	17
2018	42.75	241	728	8
2019[b]	42.75	280	451	4

[a] Exceedance Day Count is the number of distinct days during which any PM_{10} monitor in the Owens Lake area experiences an exceedance of the 24-hour NAAQS for PM_{10}.
[b] Partial year January to June 2019.
SOURCE: Holder, 2019a; Logan, 2019c.

of DCMs over greater spatial areas with time (Figure 1-3). The maximum 24-hr average PM_{10} concentration decreased from 20,750 micrograms per cubic meter (μg/m^3) in 2001 to 728 μg/m^3 in 2018. The total number of exceedance days has decreased from 49 days in 2002 to 8 in 2018. The average exceedance PM_{10} concentration has also decreased from more than 1,000 μg/m^3 in 2000 to fewer than 241 μg/m^3 in 2018. Although the DCMs have been effective, certain locations continue to experience exceedances. Thus, further effort is required to bring the region into compliance with the NAAQS for PM_{10}.

Figure 2-4 shows the variation of exceedances per year at Keeler. Similar to Table 2-1, this figure illustrates improvement over the years, although there have been large year-to-year fluctuations. The fluctuations are likely related to the variation in meteorological conditions that drive emissions, and in the erodibility of the lake surface and off-lake areas. Careful study of the drivers of variability will be critical to management of PM_{10} control practices in the future.

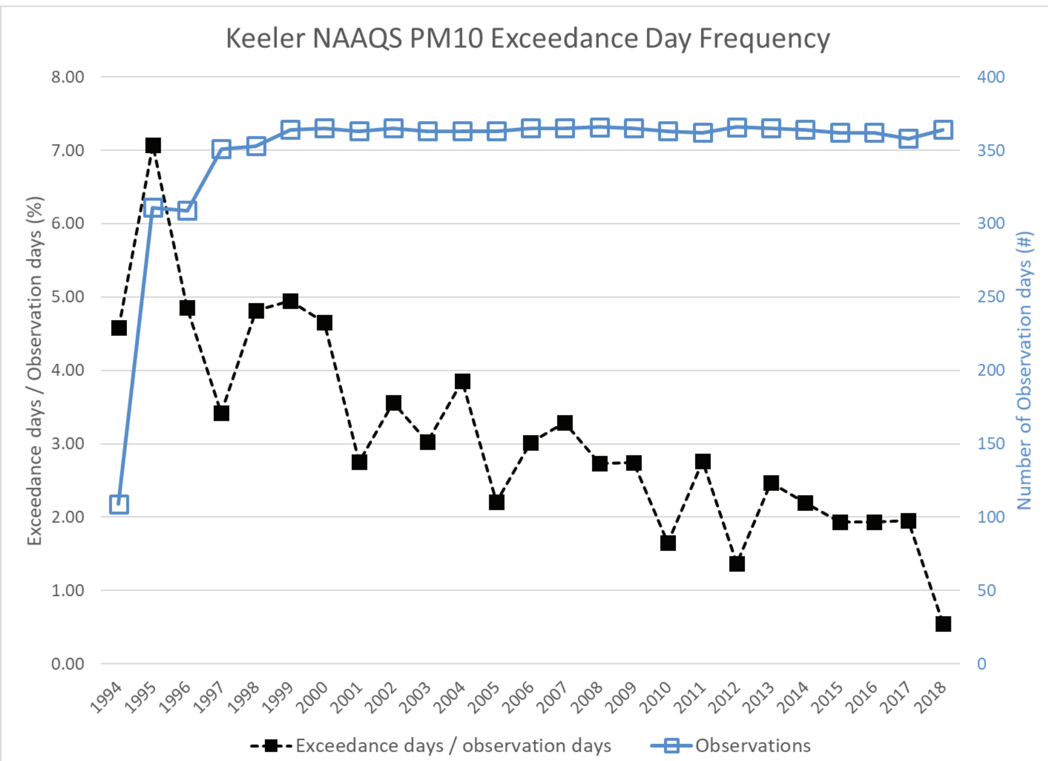


FIGURE 2-4 PM_{10} observations at the Keeler monitoring site from 1993 to 2018 showing a decrease in the percentage of exceedance days over time at this one location. The number of observation days used to calculate the percentage is shown with open squares.
DATA SOURCE: Logan, 2019c.

PM_{10} Monitor Site	From-the-Lake Wind Dir. (Deg.)	Non-lake Wind Dir. (Deg.)
Lone Pine	126≤WD≤176	WD<126 or WD>176
Keeler	151≤WD≤296	WD<151 or WD>296
Flat Rock	224≤WD≤345	WD<224 or WD>345
Shell Cut	WD≥227 or WD≤ 33	33<WD<227
Dirty Socks	WD≥234 or WD≤50	50<WD<234
Olancha	WD≥333 or WD≤39	39<WD<333
Bill Stanley	WD≥349 or WD≤230	WD<349 or WD>230
Lizard Tail	128≤WD≤288	WD<128 or WD>288
North Beach	55≤WD≤250	WD<55 or WD>250
Mill Site	157≤WD≤333	WD<157 or WD>333

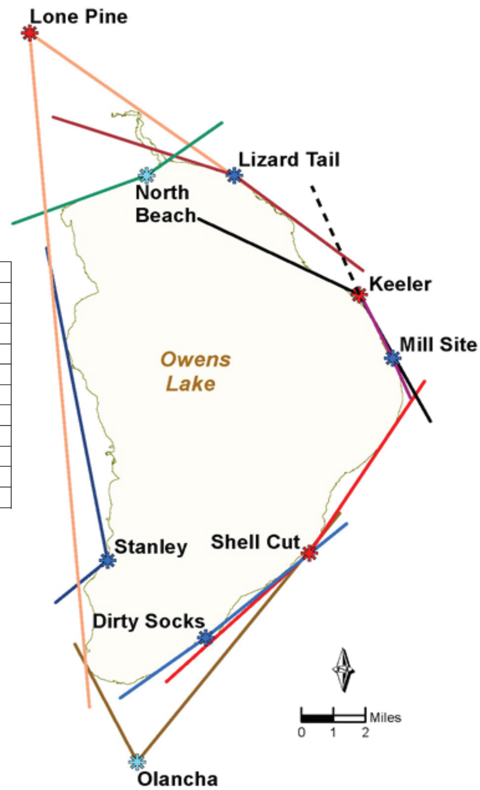


FIGURE 2-5 Variation of mean hourly PM_{10} concentrations at Dirty Socks and Keeler with wind speed.
NOTE: PM_{10} means correspond to values in the 2 m/s interval surrounding each point in the plot. Error bars show the standard error of the mean calculated as (2 × standard deviation)/√(number of data points)
DATA SOURCE: Logan, 2019c.

Figure 2-5 illustrates how mean hourly PM_{10} varies with wind speed for two different years and two sites (Dirty Socks and Keeler), and thereby the linkage of high winds to PM_{10} concentrations. Both sites reported the expected increase in concentrations with wind speed. However, the patterns of decrease differed between the sites: At Dirty Socks, greater reductions in PM_{10} concentrations occurred from 2000 to 2017 at increased wind speed, while at Keeler those reductions varied less with wind speed. An understanding of the processes that govern this behavior—informed by more sampling with distributed sensors (Li et al., 2019) and better modeling approaches (discussed later)—will support formulation of strategies to attain the NAAQS.

Although the number of exceedances has clearly decreased over the past two decades, attainment of the NAAQS and the California standards has not yet occurred. Further, the exceedances often result in high PM_{10} concentrations. For the past 3 years, the maximum

PM_{10} concentrations are from 3 to more than 10 times the level of the NAAQS, suggesting that considerable emissions reductions are still required.

PM_{10} EMISSIONS ESTIMATION

As part of its efforts to identify dust sources at Owens Lake that can cause or contribute to exceedances of the NAAQS for PM_{10}, the District uses sand flux measurements to estimate PM_{10} emissions from the lakebed and off-lake. Sand flux (more generally referred to as horizontal sediment transport) is a measurement of the mass of windblown sand-sized particles moving above the surface per unit time. Estimation of PM_{10} emissions based on surrogate sand flux measurements involves the use of a semi-empirical relationship that relies on the horizontal movement of particles, whose sizes include diameters greater than 10 µm.

The link between saltation and the emission of fugitive dust containing PM_{10} may be approximated by

$$F_a \sim Kq \qquad \text{(Equation 2-1)}$$

Where:

F_a is the PM_{10} emission rate in $g/cm^2 \cdot s$,
K (also known as the K-factor) is a dimensionless constant dependent on surface physical and chemical characteristics, and
q is the horizontal sand flux measured in $g/cm^2 \cdot s$ (Gillette et al., 2004; Ono et al., 2011).

Sand flux is measured at Owens Lake using a combination of collocated devices to measure hourly sand flux rates (see Figure 2-6). The instruments are positioned with their sensors or inlets 15 cm (5.9 inches) above the surface. Cox Sand Catchers are passive collection instruments that capture windblown, sand-sized particles (see Figure 2-7) and provide a mass collection amount for a certain sampling period (usually about 1 to 3 months). As battery-powered, sand motion detectors, the Sensit device time-resolves the collected mass to estimate hourly sand flux rates (see Figure 2-7). This device measures the particle counts of sand-sized particles as they saltate, or bounce, across the surface.[3]

Sand flux monitors at about 200 locations are used to estimate dust emissions and thus source emission rates from the lakebed (see Figure 2-8). There is a new effort to leverage the growing capabilities of inexpensive PM sensors on the lake, but this effort is limited in the number of instruments, their spatial distribution, and the duration of the effort.

[3] For additional information on sand flux measurement methods at Owens Lake, see GBUAPCD (2013c, Attachment C).

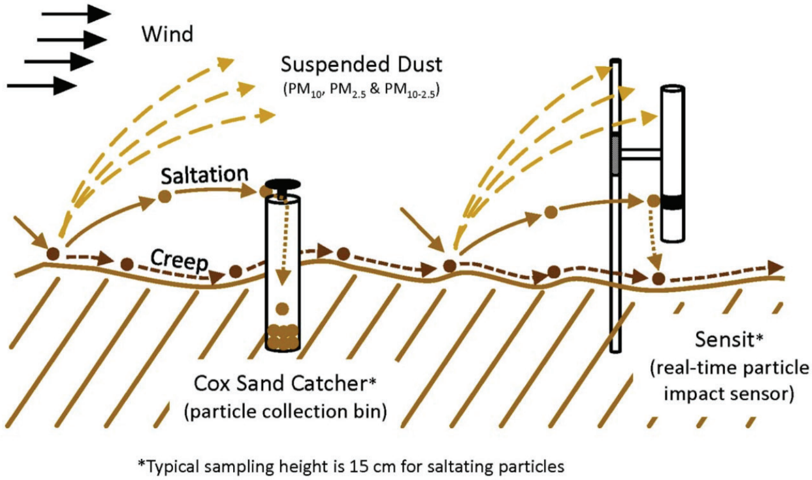


FIGURE 2-6 Illustration of sand flux monitoring site using a Cox Sand Catcher to collect sand-sized particles and Sensit that detects saltating particles.
SOURCE: EPA, 2019b.

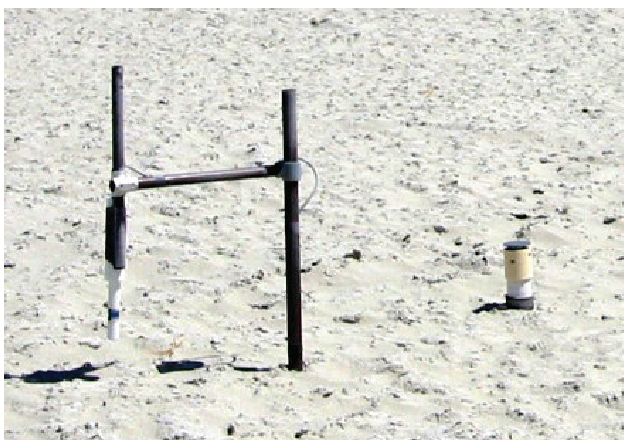


FIGURE 2-7 Photographic image of a Sensit device suspended above the ground (left) and a Cox Sand Catcher (right).
NOTE: The Sensit is a battery-powered motion detector used to count sand-sized particles per unit time that saltate (bounce) across the surface. The Cox Sand Catcher is a passive device used to capture samples of wind-blown, sand-sized particles of dust at a specific height above the surface.
SOURCE: Richmond, 2019.

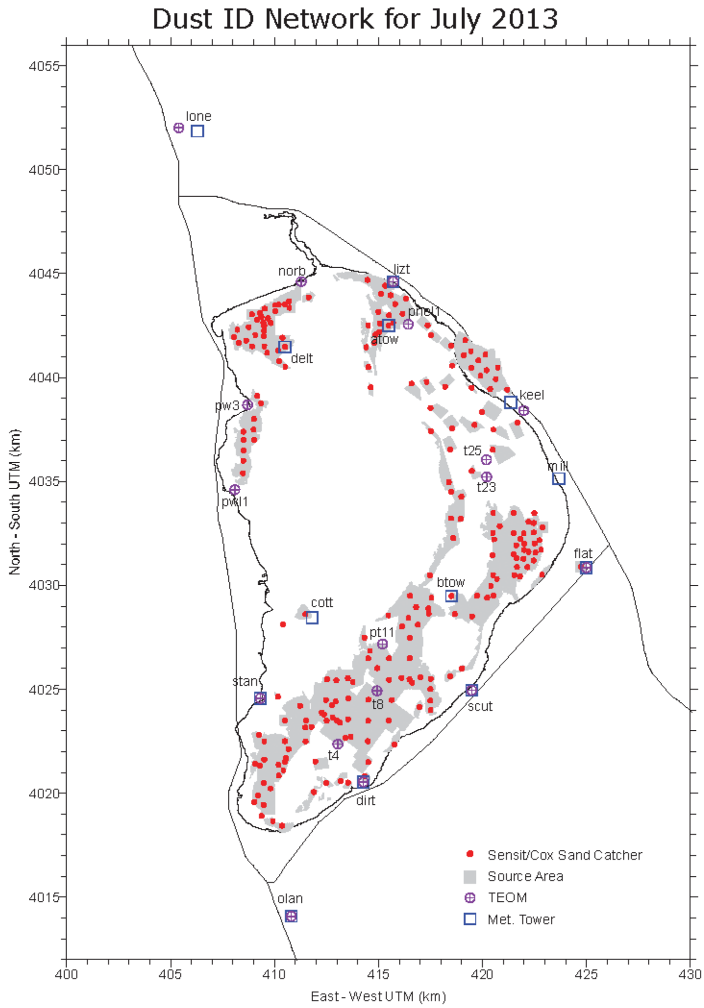


FIGURE 2-8 Locations of sand flux monitors used to estimate PM_{10} emission rates and DCM effectiveness. SOURCE: Richmond, 2019.

Use of measured horizontal sand flux to estimate PM_{10} emissions leads to uncertainty because of the spatial and temporal variability in surface conditions, which are not well represented by a constant *K* factor (Klose et al., 2019; Kok et al., 2014). The approach to estimating emissions is useful if the *K* factor does not vary significantly with the surface condition and the wind speed. However, Gillette et al. (2004) indicate that the *K* factor varies by as much as an order of magnitude, for the same surface type because of variations in surface condition and wind speed, and can vary by many orders of magnitude among surface types.

Uncertainty in the measurement of the sand flux, *q*, is also large. The Cox Sand Catcher, as used at Owens Lake, (Ono et al., 2003) is a method used for the measurement of sand flux, with lower efficiency than the samplers used by Gillette et al. (1997). The operating principle also indicates that larger particles may be preferentially trapped (Goosens et al., 2000). Although horizontal sand flux provides useful information on the susceptibility of a surface to wind induced emissions, it does not provide accurate quantitation of PM_{10} emissions. The substantial uncertainty in the use of proxy measures, such as horizontal sand flux, to estimate PM_{10} emissions, suggests additional methods be investigated to quantify PM_{10} emission from individual dust control areas.

There are several portable, real-time instruments for monitoring airborne PM, and recent advances have led to the development of low-cost and yet accurate sensors for real-time measurement of both $PM_{2.5}$ and PM_{10} (Bulot et al., 2019; Carvlin et al., 2017; Chung et al., 2001; Johnson et al., 2016; Li et al., 2019; Manikonda et al. 2016). The networking of real-time, low-cost PM_{10} monitoring devices with existing PM_{10} monitors on Owens Lake could potentially enable more accurate and precise PM_{10} measurements, made upwind and downwind of dust control areas, with enhanced spatial and temporal resolution. A network of PM_{10} sensors along the edges of contiguous dust control areas would allow for better quantification of mean PM_{10} emission rates and DCM control effectiveness, for example, by using differencing and other inverse modeling techniques. Further, time series of PM_{10} measurements collected under varying surface and meteorological conditions will enhance knowledge of how those conditions affect PM_{10} emissions and better inform management decisions.

The South Coast Air Quality Management District of California provides the results of performance assessments of low-cost sensors under field and laboratory conditions (SCAQMD, 2019). Under field test conditions (that did not include testing at Owens Lake), side-by-side comparisons of PM_{10} sensors with FRM/FEM instruments yielded R^2 results ranging from less than 0.25 to 0.66-0.70. The values on the high end of the range are promising because they indicate reasonable agreement between the sensor readings and the FRM/FEM readings.

Given the varied performance of the current generation of low-cost PM_{10} sensors, it is important to calibrate and test all devices for representative operation under the field conditions encountered on and around the Owens Lake bed. Testing should include

- Multiple types of sensors and potential sampling strategies;
- Sites on the lakebed with different soil textures and during different seasons; and
- Proximity to a meteorological site to obtain observations (e.g., humidity and radiation loading) for characterizing local environmental conditions.

In addition, there should be a transition period during which the deployment of a network of PM_{10} sensors overlaps with the use of the current network of Sensits and Cox Sand Catchers to determine relationships between the historic sand flux measurements and more directly determined PM_{10} emissions.

APPORTIONING ON-LAKE AND OFF-LAKE SOURCES OF PM_{10} EMISSIONS

According to the District, the primary sources of windblown dust in the OVPA include the Owens Lake bed, Keeler Dunes, Olancha Dunes, and other areas close to the regulatory shoreline. Other sources include small mining facilities, areas near the communities of Lone Pine and Independence, intermittent sources near the lakebed caused by flash flood deposits, and regional-scale weather events. Based on an assessment of monitoring and modeling data, the District determined that emissions from off-lake sources more than 2 kilometers away from the lakebed do not have an impact on achieving attainment of the NAAQS (GBUAPCD, 2016).

Historically, the Owens Lake bed has been the major source of windblown dust in the OVPA. However, since the implementation of DCMs nearly 20 years ago, emissions from the lakebed have been decreasing. According to the District, the Keeler Dunes, Olancha Dunes, and other sources of windblown dust near the shoreline now compose a larger fraction of airborne PM_{10} on days exceeding the NAAQS. Off-lake PM_{10} emissions continue to pose the largest challenge for demonstrating attainment of PM_{10} air quality standards within the OVPA (GBUAPCD, 2018).

The role of off-lake sources is illustrated by PM_{10}-Wind velocity plots, such as that shown in Figure 2-9 for the Dirty Socks monitor located at the southern edge of the lake. The plots in the figure show the direction from which the wind is blowing, wind speed, and resulting PM_{10} concentrations. The plots also show that the source regions for Dirty Socks in 2002 were located in the quadrants to the west and north and that hourly concentrations greater than 500 $\mu g/m^3$ occurred primarily when the wind speeds were greater than 10 m/s (22.4 mph). These observations highlight the dominant role of PM_{10} sources on the lake. With emission controls established by 2017, Figure 2-9 illustrates that, based on Dirty Socks monitoring data, the dominant source regions are primarily in the south with winds greater than 10 m/s leading to high concentrations, suggesting the importance of off-lake sources.

These results, although based on limited data, suggest that control strategies will need to place greater emphasis on off-lake sources to achieve attainment of NAAQS for PM_{10}. To bring the region into compliance, the impact of specific source regions must be firmly understood. More thorough analyses of wind speed and wind direction, coupled with dispersion models, would help to identify regions (sources) and inform the development of effective control strategies. If feasible, back trajectories could help to identify the specific source areas and emissions of PM_{10} during exceedances, and better determine whether the event is primarily driven by on-lake or off-lake emissions.

STATE IMPLEMENTATION PLAN DEVELOPMENT AND AIR QUALITY MODELING

Because the OVPA is a nonattainment area, California is required to develop a SIP that lays out a path for attainment of the NAAQS. In this case, California has delegated that task to the District. The SIP developed by the District must be approved by both California

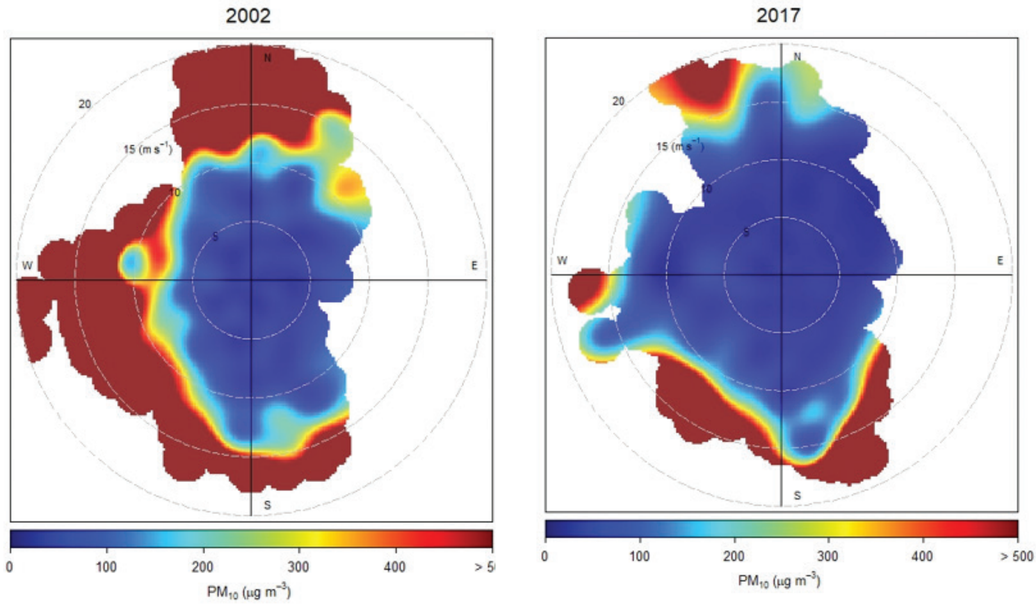


FIGURE 2-9 PM_{10}-Wind velocity plots for the Dirty Socks monitoring site in 2002 and 2017 constructed using hourly PM_{10} concentrations.
NOTES: Source regions are identified by compass directions, and the associated wind speeds in m s^{-1} correspond to the radii of the circles. The color indicates PM_{10} concentrations in µg m^{-3} (µg/m^3). Concentration distributions vary with wind direction, and concentration magnitudes increase rapidly with wind speed. The distribution of PM_{10} concentrations across the color scale can affect the transition from one color to another. Sharper transitions occur when there are larger gaps between concentration values. Looking at the 2017 plot, the blue area, representing lower PM_{10} concentrations, occurs at lower wind velocities (i.e., nearer the center of the circle). Much of the high PM_{10} concentrations (brown) occur at higher wind velocities (15-20 m/s) when the wind is coming from the south, north, or northwest, with a smaller fraction coming from almost due west. Those results suggest the importance of off-lake sources.
DATA SOURCE: Logan, 2019c.

and EPA. Developed in 1998, the first PM_{10} SIP for the Owens Lake area proposed attainment by 2006, which was not achieved. The continued nonattainment in the region has led to additional SIPs and SIP revisions in 2003, 2008, 2011, 2013, and 2016.

Air quality models play a central role in determining the amount of PM_{10} emission reductions that will be needed to bring about compliance with the NAAQS. The 2016 SIP approved by EPA concluded that "Air quality modeling has shown that this [proposed control] strategy can reduce PM_{10} impacts at sites above the regulatory lake shore to below the federal 24-hr PM_{10} standard by the end of 2017" (GBUAPCD, 2016a, p. S-15). That reduction was not achieved.

A major feature of a SIP is demonstration of attainment that involves air quality modeling. The type of air quality model applied depends on the pollutant, and EPA provides guidance for

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

model choices (EPA, 1996). Typically, a specific model is applied to prove its ability to reproduce historical airborne pollutant concentrations, and then alternative emissions levels are simulated to reflect the results of controls being applied to sources or source regions in the modeling domain. For the Owens Valley SIPs, the modeling approach has evolved, and the 2016 SIP applied a hybrid approach based on the CALPUFF/CALMET (version 6.4) modeling system (Allwine et al., 1998; GBUAPCD, 2016a; Scire et al., 1990). CALPUFF is a multilayer dispersion model without chemical reactions, which is appropriate for modeling PM_{10}, particularly over the time and distance scales involved here. As noted by EPA (2018), CALPUFF was de-listed as an EPA preferred model in its 2017 guidelines on air quality models for regulatory application, because the model was considered by the agency to no longer be needed. Although usually used for longer-range transport (more than 50 km [31 miles]), it can be used for shorter-range dispersion modeling when the three-dimensional (3-D) features of the winds are viewed as important. Otherwise, steady-state dispersion models (e.g., AERMOD; Cimorelli et al., 2005) are often used. Winds in the Owens Lake area can be complex, varying rapidly in space and time, because of the topography (e.g., the Sierra and other surrounding mountains). As a hybrid application, CALPUFF can use observations to estimate the impact of off-lake sources. CALPUFF was also updated to allow for more finely resolved emissions inputs to reflect the rapidly changing emissions estimated from sand flux measurements.

Critical inputs into the air quality modeling include the meteorology and the emission flux. Meteorological characteristics are monitored throughout the lakebed and surrounding areas (e.g., to obtain upper air variables) and are processed using CALMET, which is a computation model based on physical processes (Scire et al., 2000). For emissions modeling in this case, the approach is multistep, first estimating emissions and then adjusting the emissions to improve model performance. As discussed previously in this chapter, dust emissions from the lakebed are estimated using a relationship proposed by Gillette et al. (1997) involving an empirical *K* factor that relates sand flux to PM_{10} emissions (Ono et al., 2011). *K* factors are first estimated based on time period and surface type and, if present, DCM. After CALPUFF is run, its results are compared to the observations, and the *K* factors are adjusted to obtain better agreement.[4] This need for adjustment suggests uncertainty in the *K* factors. Given the linearity of the system, the uncertainties in the *K* factors will propagate to uncertainties in the simulated concentrations. The accuracy of air quality models would benefit from direct quantification of DCM effectiveness with far more certainty than is currently achieved using horizontal sand flux as a surrogate for PM_{10} emissions. The importance of accurate estimates of a DCM's effectiveness in controlling PM_{10}, and improved estimates of associated uncertainties, increases as airborne PM_{10} concentrations approach the allowable level of the air quality standards.

[4] Further details of how the *K* factors are derived are provided in the 2016 SIP (including Appendix VII-1).

In this type of application, the credibility of the air quality model must be established; in this case by showing that the model adequately captures historic observations, with a specific focus on conditions leading to exceedances. Then the model is run to determine the level of emission control required to attain the NAAQS for PM_{10}. The model is assumed to be a virtual surrogate for the real system. The model allows for numerical experiments to be conducted that would be impractical to be carried out in the real system.

The modeling approach presented to the panel can be improved significantly. For example, Richmond (2019) indicated that the model often does not explain the temporal variability of the observations. Furthermore, the model did not estimate 40 of the 194 exceedances of the NAAQS observed during July 2009 to June 2014. The evaluation results of the model presented in Richmond (2019) focused on days for which the measured average concentrations were greater than 150 $\mu g/m^3$, based on the assumption that good performance of a dispersion model for predicting high concentration days lends credibility to the model's ability to predict NAAQS attainment. However, it is also necessary to assess the model's performance when it estimates concentrations greater than 150 $\mu g/m^3$ but the observed concentrations are lower than the NAAQS level. Such an assessment is important because attainment demonstration requires estimating PM_{10} concentrations that are less than the NAAQS level or when observations are not available.

Model performance and hence the reliability of future projections of air quality can be improved by paying more attention to the processes that dominate emissions and dispersion during high winds, when the highest PM_{10} concentrations occur (see for example, Shiyuan et al. 2008). The modeling of vertical dispersion can be improved within the framework of CALPUFF by using dispersion coefficients based on internally calculated micrometeorological variables rather than the Pasquill-Gifford curves formulated more than 60 years ago. Better still, dispersion curves that are specifically formulated for near surface releases and reflect the current understanding of dispersion and micrometeorology (Cimorelli et al., 2005) could be used. This option requires expressing model inputs in terms of variables, such as friction velocity, which controls dispersion as well as emissions. Those variables can be measured using a 3-D sonic anemometer or estimated with the CALMET processor. Efforts to improve the dispersion model and its inputs to reflect the state of the art and then to evaluate against observations would better inform decision making on emission control related to NAAQS attainment. It is also important to identify, and to the extent feasible quantify, the sources of uncertainty in the model. See NRC (2007) for a discussion of quantifying and communicating uncertainties.

CONCLUSIONS AND RECOMMENDATIONS

This section presents the panel's key conclusions and recommendations concerning progress in managing airborne PM_{10}, quantifying PM_{10} emissions, and air quality modeling.

Progress in Managing Airborne PM_{10}

Conclusion: Because of the efforts of the District and LADWP, airborne PM_{10} concentrations at monitoring locations in the OVPA have decreased significantly since the implementation of DCMs on Owens Lake.

Quantifying PM_{10} Emissions

Conclusion: Estimates of reductions in PM_{10} emissions are associated with a high degree of uncertainty because they have relied primarily on measurements of sand flux. The size-dependent performance and other measures of sampling efficiency are not available for the Sensits and Cox Sand Catchers, which are used to measure sand flux. The *K*-factor values imputed by the observations are highly variable, greatly impacting estimated current and future emissions.

Conclusion: Increased use of low-cost sensors and other advanced PM monitoring techniques would help to characterize the location and magnitudes of the high source regions, further helping to quantify the control efficiencies of the DCMs being utilized on and around the lakebed.

Recommendation: The District and LADWP should develop and apply additional methods to quantify, with uncertainty estimates, PM_{10} emissions from individual dust control areas, based on direct measurements of airborne PM_{10} concentrations.

All devices should be calibrated and tested for representative operation under the field conditions encountered on and around the Owens Lake bed. Testing should include

- Multiple types of sensors and potential sampling strategies;
- Sites on the lakebed with different soil textures and during different seasons; and
- Proximity to a meteorological site to obtain observations (e.g., humidity and radiation loading) for characterizing local environmental conditions.

In addition, there should be a transition period during which the deployment of a network of PM_{10} sensors overlaps with the use of the current network of Sensits and Cox Sand Catchers to determine relationships between the historic sand flux measurements and more directly determined PM_{10} emissions.

Air Quality Modeling

Conclusion: The panel recognizes the complexity of the processes that govern PM_{10} emissions from the Owens Lake area and the subsequent transport and dispersion of those emissions. However, the modeling approach used to demonstrate attainment of the NAAQS for PM_{10} does not use state-of-the-art dispersion formulations.

Conclusion: The modeling conducted as part of the 2016 SIP would be improved with increased evaluation and uncertainty analysis, as suggested by the National Research Council report *Models in Environmental Regulatory Decision Making* (NRC, 2007).

Conclusion: Given the continued nonattainment in the OVPA, additional analysis and documentation of the failure of past emission control strategies are needed.

Recommendation: Approaches to air quality modeling to demonstrate attainment of the NAAQS for PM_{10} should incorporate the current understanding of micrometeorology and dispersion, especially during periods of high winds. Particular attention should be given to characterizing the conditions leading to exceedances, and identifying major source locations both on- and off-lake. Furthermore, the uncertainty associated with modeling those processes should be factored into plans to attain the NAAQS.

3

Natural Resources and Environmental Context

The natural setting at Owens Lake both influences and is influenced by decisions concerning dust control. A complex array of factors related to climate, hydrology, habitat conservation, mining, and cultural resources provide an important context for evaluating dust control measures (DCMs). In this chapter, the committee discusses key factors within this broad context with implications for dust management.

CLIMATE, HYDROLOGY, AND WATER RESOURCES

The Owens Lake watershed is a closed basin located on the east of the Sierra Nevada and western edge of the Great Basin, at the southern end of the Owens Valley (Smith and Bishoff, 1997) (see Figure 3-1). The presence of the Sierra Nevada range to the west results in a significant precipitation shadow (Danskin, 1998). Owens Lake receives limited precipitation and significant sunshine, with generally low humidity that results in high potential evapotranspiration. The 50-year average annual rainfall on the valley floor is 6.22 inches, while the average annual snowfall at high elevations in the watershed at the Mammoth gauge is about 43 inches (as snow water content; Duell 1990; Hollett et al., 1991; LADWP, 2019a). Figure 3-2 highlights long-term cyclicity in the precipitation record—in recent years typically consisting of a few years of above average precipitation followed by 3-5 years of below average precipitation.

The Owens Valley drains an area of approximately 3,300 square miles, and the hydrologic system in the valley consists of surface water and groundwater. Both have been significantly altered by water extraction over the past century through surface water diversions from the Owens River to the city of Los Angeles and groundwater pumping in the valley.

Surface Water

The complex and altered surface water system of the Owens Valley includes the Owens River, tributary streams, the Los Angeles Aqueduct, reservoirs, interbasin transfers from the Mono Lake watershed, and Owens Lake itself (see Figure 3-1). The long term (48-year) surface

FIGURE 3-1 Overview of the Owens Valley water system.
NOTES: The Owens Valley is shown in green, but the headwaters of the Owens Valley include diversions from the Mono Lake Basin (shaded brown) via the Mono Craters Tunnel. The Los Angeles Aqueduct begins south of the Tinemaha Reservoir, about 40 miles north of Owens Lake.
SOURCE: Edited based on https://www.usgs.gov/centers/ca-water/science/owens-valley-hydrogeology (accessed January 28, 2020).

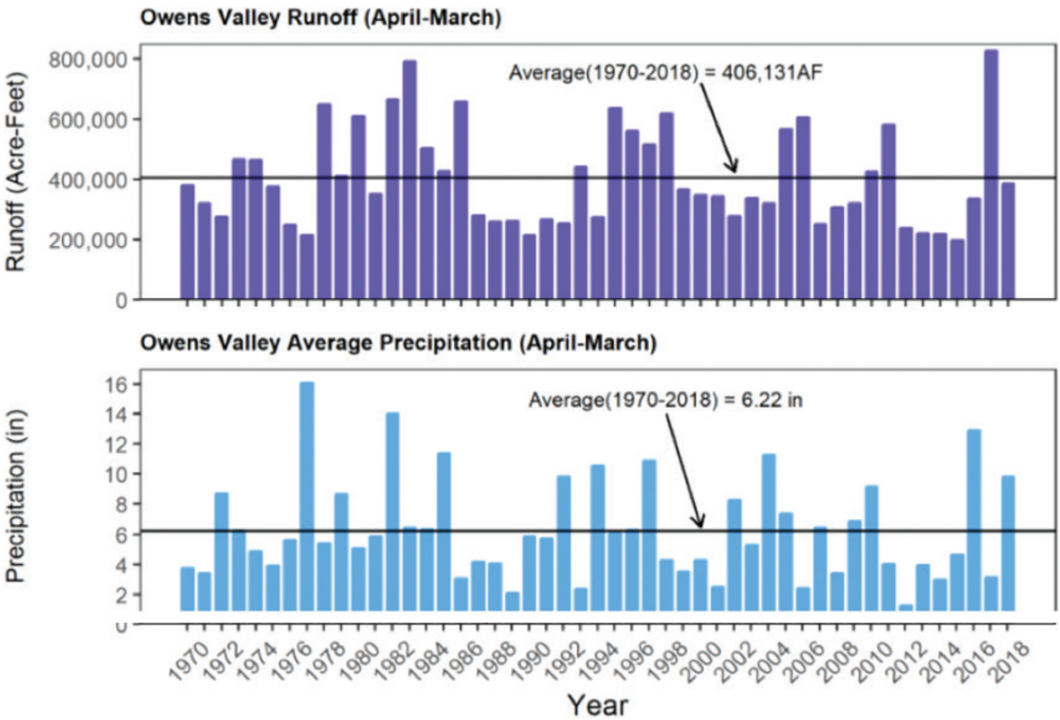


FIGURE 3-2 Summary of historic Owens Valley hydrology conditions. The upper figure represents the estimated annual runoff from Owens River watershed, based on snow course and measured flows. Note that the Mono Basin diversions are not included in this graphic). The lower figure documents the annual precipitation from measurements on the Owens Valley floor near Owens Lake.
SOURCE: LADWP, 2019a.

runoff in the basin averages 406,000 acre-ft/year, but Figure 3-2 shows the strong variability in precipitation and water runoff in the Owens Valley. During drought years (2015 for example) runoff was about half the long-term average, while in 2017, runoff was approximately double the average.

Since 1913, the vast majority of surface water flows, which once sustained Owens Lake as a closed-basin lake, have been diverted into the Los Angeles Aqueduct. This diversion led to desiccation of the lakebed by 1926. The present Owens Lake consists of large areas of exposed lakebed and a region of brine-saturated surficial salt deposits known as the "brine pool," which has nearly 30 percent salinity (increased from approximately 6-7 percent prior to diversions) (Herbst and Prather, 2014; Ver Planck, 1959).

The Los Angeles Aqueduct exports surface water along with additional water from groundwater pumping out of the Owens Valley (see Figure 3-1). The aqueduct begins about 40 miles north of Owens Lake and consists of more than 200 miles of canals, tunnels, and conduits. During typical climatic conditions, only a small amount of water is discharged into Owens Lake, which sustains the brine pool and appropriate conditions for mining (see Mineral Resources later in this chapter). Recently, only during the wettest years (e.g., 2017) when aqueduct capacity is exceeded, does significant surface runoff reach Owens Lake. Under extreme flood conditions, unmanaged flows can enter Owens Lake from the north through the Owens River or via numerous smaller mountain drainages to the east or west of the lake. Water for the DCMs at Owens Lake is supplied by the aqueduct.

Between 1950 and 1970, approximately 300,000 acre-ft/year was consistently exported to Los Angeles via the aqueduct. By 1971, those exports increased with an expansion of the aqueduct capacity. However, in the past 30 years, multiple legal challenges, including disputes over Mono Lake diversions and concerns over groundwater over-pumping, and several severe droughts have significantly affected both the availability and export of water (see Figure 3-3). Since 1994, when minimum flows into Mono Lake were established, flows in the Los Angeles Aqueduct have ranged from a low of 58,000 acre-ft/year to a high of more than 450,000 acre-ft/year. The average annual supply from the Los Angeles Aqueduct since 1994 is approximately 250,000 acre-ft/year, although average supplies over the past decade when California experienced a multiyear drought dropped to 170,000 acre-ft/year (Valenzuela, 2019b).

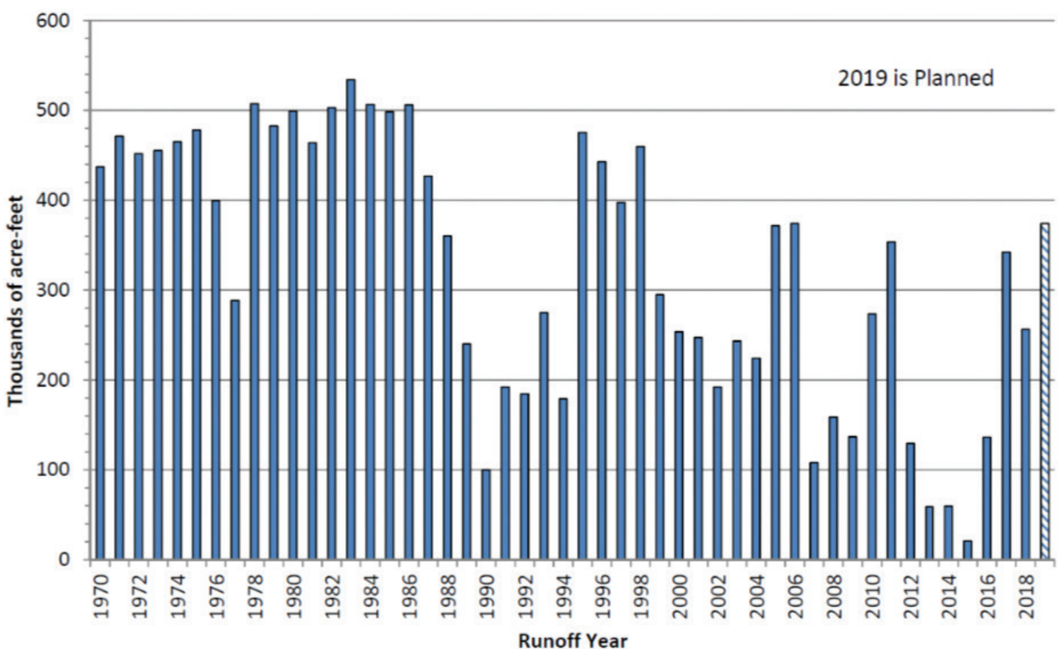


FIGURE 3-3 Water exports via the Los Angeles Aqueduct from 1970 to 2018.
NOTE: These totals do not include water used for dust management at Owens Lake.
SOURCE: Solis, 2019.

Groundwater

Both shallow and deep groundwater upgradient in the Owens Valley and at the margins of Owens Lake is generally fresh. Groundwater is used locally for municipal water supply in Owens Valley communities, for agriculture, and for commercial bottled water production. Shallow groundwater (<50 feet) directly beneath Owens Lake is saline to hypersaline, reflecting the evaporation and concentration of salts that occurred in recent history and following the diversion of the Owens River and subsequent near desiccation of Owens Lake. Deeper groundwater beneath the lake ranges from brackish to near seawater salinities and represents fossil groundwater associated with higher lake stands through the Pleistocene (Smith and Bischoff, 1997).

On the lakebed, shallow groundwater is generally close to the surface (Tyler et al., 1997), with reported depths between 3 and 8 feet. Springs and seeps can be found on the margins of the lake at the base of alluvial fans (see Figure 3-4). A few artesian wells exist on the lakebed that tap into confined aquifers.

The depth to shallow groundwater at Owens Lake likely varies on annual and longer time scales. However, as is common on many saline playas, the shallow groundwater table beneath the lakebed generally remains below the land surface. The geologic material that makes up the lakebed ranges in texture from coarse sand to salt-crusted clay sediments (Tyler et al., 1997; see Figure 4-7). Evaporation from the groundwater is limited by either the coarse texture of some of the surface material or the presence of salt crusts. Tyler et al. (1997) reported annual

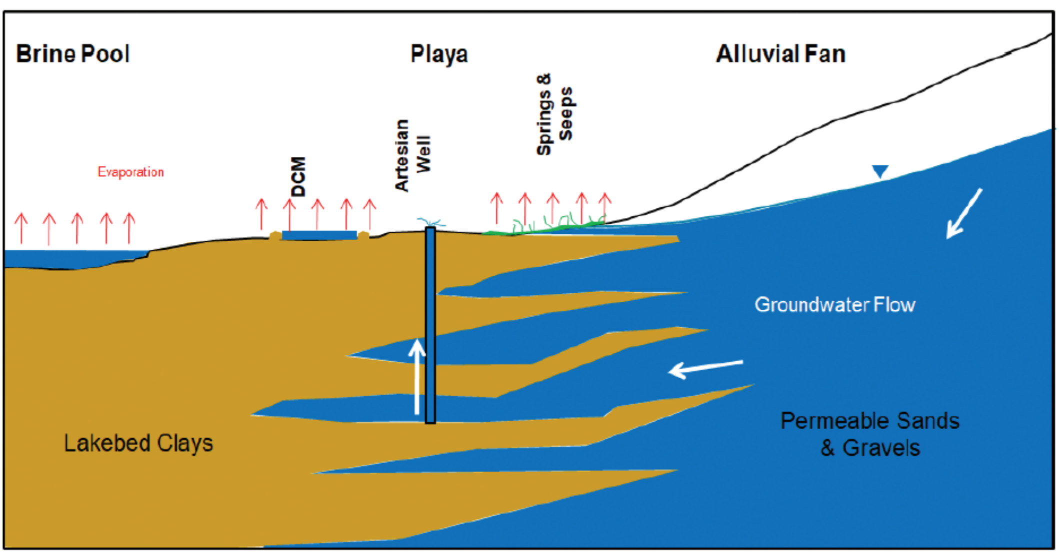


FIGURE 3-4 Conceptual diagram of groundwater at Owens Lake.
SOURCE: Jorat, 2019.

evaporation rates from the groundwater table at several different areas of the dry lakebed to be quite low, ranging from 88-104 mm/yr (3.5-4.1 inches/yr). Although small, capillary-driven evaporation combined with the presence of saline shallow groundwater in many areas of the lakebed leads to the development of salt crusts and salt-cemented sands near the surface. Total lakebed evaporation would also likely include most of the annual precipitation falling on the lakebed as suggested by Malek et al. (1990).

An increase in groundwater pumping in the Owens Valley between 1970 and 1984 led to an overdraft of the groundwater basin and a sizable drop in groundwater levels, primarily in the northern half of the Owens Valley (Danskin, 1998), which led to loss of groundwater-dependent vegetation (Elmore, 2003; LADWP, 2019a). This habitat loss led to active enhancement and mitigation efforts by the Los Angeles Department of Water and Power (LADWP) and gradual reduction in groundwater pumping. In 1991, the county of Inyo and the LADWP agreed on a long-term management plan.[1] The plan, which has since been supplemented by additional agreements, limited rates of withdrawal for LADWP considering local groundwater recharge rates and withdrawals from other users to mitigate impacts of groundwater mining (LADWP, 2019a). Since 2000, LADWP has pumped on average 70,000 acre-ft of groundwater annually from the Owens Valley (LADWP, 2019a). LADWP is currently investigating the potential use of groundwater withdrawn from beneath Owens Lake for dust control efforts as part of the Owens Lake Groundwater Development Program using an adaptive management approach.[2] Additional detail on Owens Valley hydrology and groundwater budgets can be found in Hollett et al. (1991) and Danskin (1998).

Owens Lake Context for Water Management

Since 2000, LADWP has been using a significant volume of water from the Los Angeles Aqueduct for dust control on the Owens Lake bed. Currently, dust mitigation on the lakebed requires approximately 65,000 acre-ft/year (average of 2017-2018; see Figure 3-5). Recent use is similar (64,000 acre-ft/year) to the long-term average use from 2007 to 2018, and all of this water eventually evaporates. Since 2007, dust control used 31 percent of available LADWP water at Owens Lake (assumed to be a total of LADWP exports in the Los Angeles Aqueduct and Owens Lake water use), with a range of about 17 to 51 percent.

The extensive dust control infrastructure is vulnerable to precipitation extremes, which have occurred recently in wet years with high snowpack (e.g., 2017) and have caused damaging flood events and multiyear droughts that created challenges for regional water supply. During the extreme drought from 2012 to 2015 in California, insufficient water was available

[1] See https://www.inyowater.org/documents/governing-documents/water-agreement/#AGREEMENT (accessed January 28, 2020).

[2] See https://ladwp.com/ladwp/faces/ladwp/aboutus/a-water/a-w-losangelesaqueduct/a-w-laa-owenslakegroundwaterevaluation?_adf.ctrl-state=6ofsp1hv3_4&_a&&_afrLoop=6445882895763 (accessed January 28, 2020).

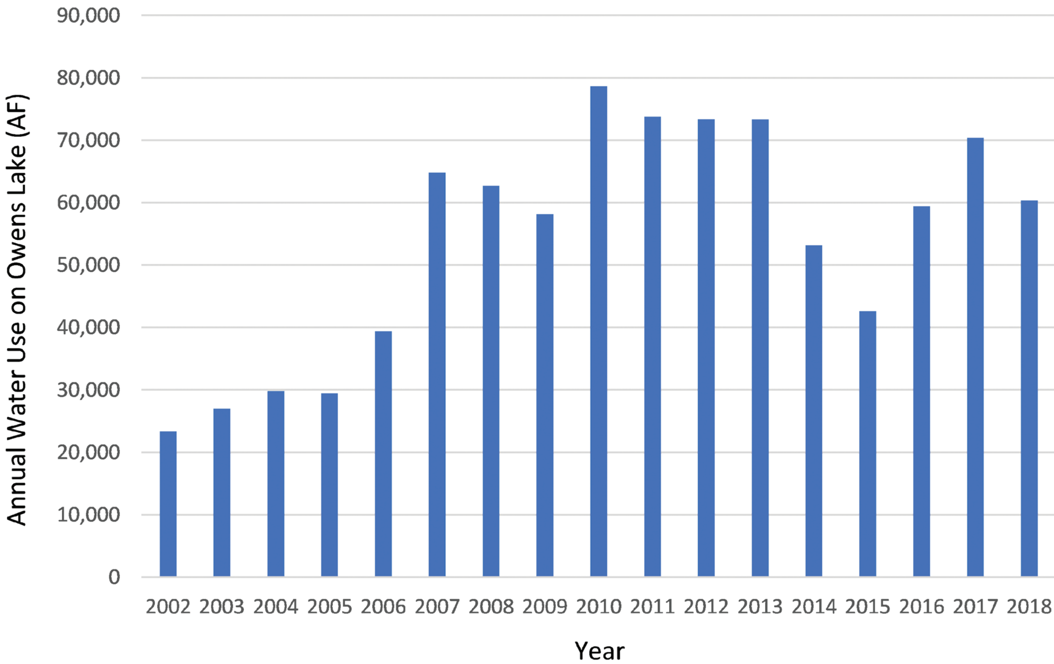


FIGURE 3-5 Annual water use on Owens Lake.
SOURCE: Valenzuela, 2019b.

to fully operate the existing Best Available Control Measures (BACMs) on the lakebed, and adjustments to the shallow flooding BACM requirements were made, including reduction of water use and changes in water application timing.

In recent years (2013-2017), water from the Los Angeles Aqueduct (including inflows from the Mono Basin) represented 19 percent of LADWP water supply sources (see Figure 3-6). Other sources include recycled water, groundwater, and imported water purchased from the Metropolitan Water District of Southern California. LADWP is working to reduce its reliance on imported water, such as water conveyed from the Sacramento Bay Delta and the Colorado River, and to increase the use of LADWP's available local water supplies, such as Los Angeles area groundwater supplemented by enhanced recharge of stormwater. Under recent strategic plans, LADWP water supplies provided via the Los Angeles Aqueduct would increase from its current 19 percent to 42 percent of LADWP's supply by 2040 (Cortez-Davis, 2018), primarily through water conservation efforts in the Owens Valley, including at Owens Lake. Owens Lake water conservation is intended to complement LADWP investments in recycled water, stormwater, and groundwater storage and additional efforts to reduce per capita water use through water conservation and efficiency projects to reach LADWP's overall water supply goals.

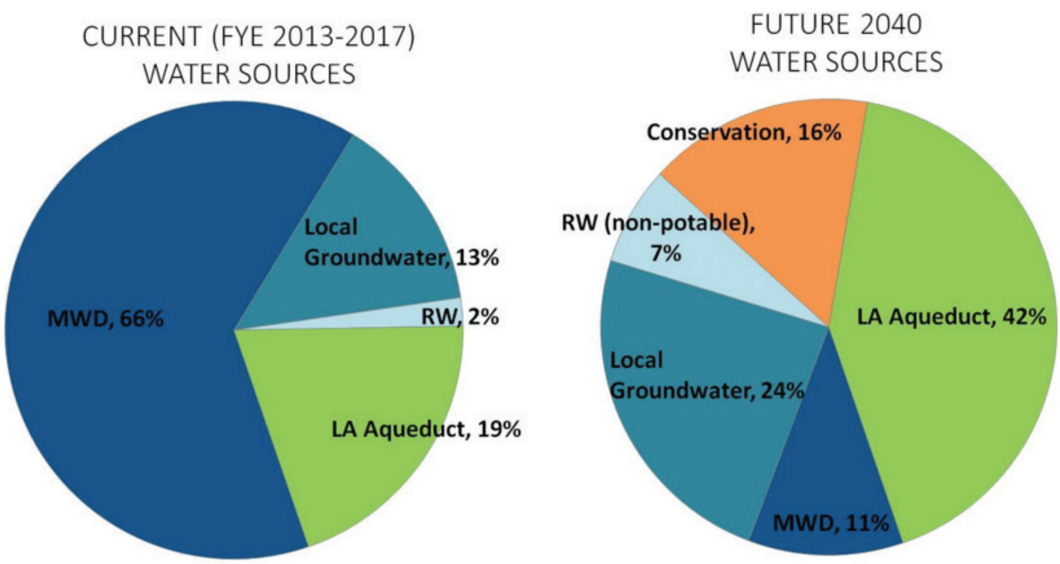


FIGURE 3-6 Recent LADWP water supply sources and water supply portfolio targets for 2040 under average year conditions.
NOTES: Average water use from fiscal years ending in 2013-2017 was 530,000 acre-ft/year, and future 2040 use is projected to be 675,700 acre-ft/year (LADWP, 2015, 2017). MWD = imported water from Metropolitan Water District; RW = recycled water.
SOURCE: Cortez-Davis, 2018.

Climate Change and Water Management

Climate change in the 21st century is expected to have significant impacts on the hydrology and water resources of California, the Sierra Nevada, which supplies runoff to the Owens River, and to the Owens Valley itself. In general, warming climates are predicted to lead to an accelerated and more variable hydrologic cycle (NASEM, 2016). In California, Hayhoe et al. (2004) predict a 73-90 percent decrease in the snowpack of the Sierra Nevada by the end of the 21st century, a trend consistent with other studies of the region (Harpold et al., 2017; Klos et al., 2014; Reich et al, 2018). Although predictions of the future annual average precipitation are less reliable, warming temperatures are predicted to result in less total runoff and streamflow generation in the eastern Sierra (Hayhoe et al., 2004; Huang et al., 2018). Runoff would occur earlier in the season, including in mid-winter because of an anticipated increase in the rain-snow transition elevation in the Eastern Sierra.

The Sierra snowpack has typically served as California's largest water storage reservoir. The water conveyance systems in the Owens Valley and in the headwaters have relatively small surface water reservoirs. Some groundwater recharge and recovery has been initiated in the Owens Valley, including surface flooding during the exceptionally high runoff year of 2017, but groundwater storage is not widely developed. Therefore, warming temperatures mean that winter rain will quickly move down the watershed to the Owens River, producing river stages that peak in late winter and very early spring. This results in a mismatch in timing of runoff and demand, which will likely have significant implications for water management and for the design and implementation of water storage in this century and beyond (see, e.g., Hayhoe et al., 2004).

Climate change is also expected to significantly increase average temperature and consequently evaporation and evaporative demand by vegetation throughout the Owens Valley watershed. Using a simplified reference evaporation model (FAO-56), a 2°C warming will increase the evaporation rate at the Owens Lake by ~3.5 percent during the current dust control season. In the watershed, warming temperatures will also lead to greater snow sublimation, evaporation from open canals and reservoirs, and increased transpiration demand by vegetation, which will likely lead to less water available for either dust control or downstream demand. This double impact—of increased water demand for Owens Lake dust control efforts and a reduced water supply for dust control—is not conjectural, but simply a fact of warming average temperatures and the physics of evaporation.

Finally, climate change is expected to lead to more and greater extreme events, at both short time scales (local flooding and heat waves) and longer ones (more prolonged and deeper droughts [Diffenbaugh et al., 2015, 2017]). Short-term extremes, such as increased convective storm intensity, could affect the dust mitigation infrastructure through local flooding and sediment transport onto the dust control areas. Over the medium to long term, prolonged droughts will further reduce the availability of water for dust mitigation and downstream water use, as was seen in 2015 when LADWP halted flow through the Los Angeles Aqueduct to ensure that legal obligations for Owens Lake dust control and Owens River minimum flows were met (Barragan, 2015). Conversely, the extreme runoff year of 2017 led LADWP to issue warnings to the communities and lake resource managers to expect significant flooding and possible damage to on-lake infrastructure.

CULTURAL RESOURCES

Native Americans are an integral part of the Owens Lake ecosystem. The area was likely first populated at least 10,000 years ago, and until approximately 700 years ago, Native Americans in the region were highly nomadic populations that largely relied on animal resources (Basgall and McGuire, 1988; GBUAPCD, 1996). Climate shifted considerably during this time period, spanning relatively cool and moist conditions to warm and dry and thereby leading to variation in the availability and location of resources (Bagsall and McGuire, 1988). During an extended dry period from 750-950 years before present, the lake was likely dry, and Native American use of Owens Lake may have extended into the playa (GBUAPCD, 1996; Stine, 1994). Over the past 700 years, the Owens Lake area has been populated by

Paiute, speaking Mono language dialects, a division of Numic-speaking cultures (GBUAPCD, 1996). Particularly during the past 600 years, until Owens River inflows were diverted into the Los Angeles Aqueduct, wetland resources increased in and around Owens Lake. The Owens Lake area became unique in the Great Basin by supporting a shift from nomadic to more sedentary lifestyles, relying on both plant and animal resources around the lake (Binford, 1980; GBUAPCD, 1996), such as waterfowl, fish, freshwater mussels, brine shrimp, brine fly larvae, grasshoppers, caterpillars, grass and chia seeds, and tubers. The rich resources of the lake, extensive irrigation to promote food plants such as nutgrass (Liljeblad and Fowler, 1986), and extensive trade supported relatively high populations of Native Americans (as high as two people/square mile) compared to other areas in the Great Basin (Delacorte et al., 1995; GBUAPCD, 1996).

The long history of Native Americans at Owens Lake spanned natural variation in the lake level, and therefore cultural resources and historically significant sites exist across a broad band around the lake that reflects changes in shoreline elevation over time (GBUAPCD, 2016a). Cultural resources at Owens Lake have generally not been identified by LADWP or the Great Basin Unified Air Pollution Control District (District) until dust control efforts begin. During construction, the discovery of cultural resources requires their assessment to determine if they are eligible for protection under the California Register of Historical Resources, California Environmental Quality Act Guidelines 15064.5[b and c]), or California Public Resources Code 21083.2. If deemed eligible, buffer areas will be established to avoid further impacts. Recommendations of all cultural areas exempted from dust control will be informed by non-binding recommendations from the Cultural Resources Task Force (GBUAPCD, 2013a). Several sites on the Owens Lake bed have been deemed eligible for deferral, which must be considered in the management of Owens Lake. The locations and details of these archaeological and sacred sites are exempt from public disclosure, according to the California Public Records Act. Under the 2014 Stipulated Judgement for Owens Lake, "cultural and biological resource protection and mitigation shall be incorporated to the extent feasible as required by law into the design of dust control areas."[3]

Local tribes who originally inhabited the Owens Valley are an integral part of the ecosystem and have a strong sense of ownership and stewardship in the valley. However, they control only a small portion of the territory they once controlled. They have requested that cultural sites are not damaged and that artifacts are not removed. Artifacts provide a tapestry of stories and traditions and are viewed as funerary out of reverence for ancestors and the traditions they handed down. Outside the context of their location, artifacts have far less significance.

[3] Stipulated Judgment in the matter of the City of Los Angeles v. the California Air Resources Board et al. Superior Court of the State of California, County of Sacramento. Case No. 34-2013-80001451-CU-WM-GDS. Approved by the court on December 30, 2014. See https://gbuapcd.org/Docs/District/AirQualityPlans/SIP_Archive/2014_Stipulated_Judgment_20141230.pdf (accessed January 28, 2020).

To this end, culturally significant sites should preserve artifacts in place so that future generations may visit the sites and learn the stories of their ancestors.

Sites determined to contain eligible cultural and historic resources (as well as a buffer around them) have been initially excluded from dust control activities, but if found emissive after surrounding dust control is implemented, may be scheduled for dust control (GBUAPCD, 2016a). Agencies are interested in identifying new DCMs that could be implemented without land disturbance or heavy infrastructure. In planning any future dust control areas beyond the current ordered areas, advance consideration of traditional focal points of cultural activities, such as springs and wetlands, could help avoid inadvertent damage of cultural resources.

The tribes have requested that culturally and historically significant sites not be subjected to heavy machinery and leveling operations typically associated with DCM construction and that LADWP and the District secure roads leading to or near the sites to minimize looting and inadvertent destruction (Bancroft, 2013).

The tribal concerns extend beyond areas containing artifacts. The diverse habitats and geographic features are also valued cultural resources and a priority for protection. In written comments that accompanied the 2016 State Implementation Plan (SIP) (GBUAPCD, 2016a), Mary Wuester, Tribal Chairperson of the Lone Pine Paiute-Shoshone Reservation, expressed support for efforts to "enforce protection of the ecological gains made despite the industrialization of the landscape" in the face of "waterless and water neutral policies" at Owens Lake. Specific locations and environments became precious to the collective and individual conscience as memories and ancestral traditions became attached to them. Legends and stories have been passed down in oral traditions to amplify and explain the significance of specific events and locations. According to Katherine Bancroft, the Tribal Historic Preservation Officer of the Lone Pine Paiute-Shoshone Reservation, "Our family's history is in the landscape. Not only are they destroying the proof of historic events and our prehistoric way of life, but they are changing the landscape and geology that our stories are built on." Leveling of land, building of roads, installation of infrastructure, and other landscape modifications adversely impact these valuable cultural landscapes (Bancroft, 2013).

HABITAT RESOURCES

As currently managed, water-based DCMs at Owens Lake provide valued habitat resources that support productive food webs, which attract a diversity of birds and other species. This section outlines the habitats that exist at Owens Lake, with additional discussion of bird conservation efforts. This context is important to understand the potential implication of expanded use of waterless and low-water DCMs, which are discussed in Chapter 4.

A broad suite of stakeholders have contributed to the environmental priorities on Owens Lake, including the public, Native American tribes, and nongovernmental organizations such as the Audubon Society and American Bird Conservancy. Two agencies—the California State

Lands Commission and the California Department of Fish and Wildlife—have oversight roles regarding the use of individual DCMs at Owens Lake as they affect environmental conditions and habitat.

The California State Lands Commission has jurisdiction over approximately 89 percent of the historic lakebed because Owens Lake used to be navigable. This Commission is responsible for public trust interests, particularly protecting and enhancing natural resources, protecting and enhancing public health and safety, and respecting and protecting Native culture, values, and resources. Its priority public trust issues on Owens Lake include wildlife habitat, public access, recreation, aesthetic enjoyment/protecting the viewshed, and cultural resources. Any management or development activity on Owens Lake requires a lease to be approved by this Commission. For example, the Commission denied the lease for the moat and row dust control measure on a 3.1 square mile area for Phase 7a, because moat and row was deemed to be inconsistent with public trust values, such as habitat, recreation, and aesthetics (CSLC, 2010).

The California Department of Fish and Wildlife oversees the Cartago Wildlife Area on Owens Lake, 218 acres of freshwater wetlands and springs that provide important bird habitat. More importantly, it has jurisdiction over Owens Lake through permitting power that implements its mandate to conserve, protect, and manage fish, wildlife, and native plants, and the habitats needed to sustain the populations of these species. On the Owens Lake bed, there is a no net loss requirement of bird nesting habitat. In addition, the department's 2010 Habitat Management Plan for Owens Lake (LADWP, 2010) requires no net loss of riparian or aquatic habitat functions, values, and acreage, with implementation of the dust control areas outlined in the 2008 SIP (GBUAPCD, 2008). The agency also has specific requirements for bird habitat management to protect shorebirds and the Snowy Plover on more than 1,500 acres of Owens Lake.

Habitats of Owens Lake

As in any arid region, the nature and distribution of habitats are strongly associated with water. Aquatic features such lakes, riparian areas, seeps, springs, and marshes provide high-value habitat for diverse plant and animal species (Fowler and Fowler, 2008; NRC, 1989; Robinson, 2018; Trimble, 1999).

After the drainage of Owens Lake but before dust control efforts began, the dry lakebed was dominated by a remnant hypersaline brine pool and unvegetated playa (see Figure 3-7). This unvegetated playa covered most of the lakebed and thus spanned highly variable conditions, with sites ranging in soil type (e.g., lacustrine clay, silt, sand) and in depth to groundwater (0-25 feet). Salt crusts generally cover the surface. The barren playa, when wet, supports diatoms and cyanobacteria that are important food sources for invertebrates. Invertebrates are the only substantial populations of wildlife on the barren playa and are

FIGURE 3-7 The unvegetated Owens Lake playa.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

largely concentrated in scarce areas of water, such as shallow pools. Invertebrate density is much higher and can support a more robust food web in perennially wet areas (LADWP, 2010). Before dust control efforts began, only 1-2 percent of the dry lakebed consisted of biologically valuable habitats such as scrub (e.g., shadscale, saltbush, and desert sink) and alkali meadows. The highest valued habitat covered approximately 412 acres (Sapphos Environmental, Inc., 2008), concentrated in scattered seeps and springs along the shoreline, and in the Delta and riparian and wetland habitats associated with the Owens River as it entered the lake (LADWP, 2010; Robinson, 2018).

Extensive use of water for dust control via shallow flooding (see Chapter 4) unintentionally created habitat for vegetation and wildlife, as demonstrated by self-recruitment of saltgrass and tens of thousands of birds. A patchwork of habitat types have been created by different dust control strategies implemented within discrete "cells" of the lakebed, overlain across a landscape that varies in salinity and other environmental factors (e.g., soil type, topography, groundwater depth) (LADWP, 2010; Robinson, 2018). This engineered landscape supports key native ecosystem types and has created a series of novel ecosystems that are important habitat for diverse species. Bird populations in particular have increased since dust control management began, with the heterogeneous mix of habitat types providing foraging and nesting habitat for more than 100 bird species, leading the National Audubon Society and American Bird Conservancy to designate Owens Lake as an Important Bird Area.

The following sections describe the key habitats of the current Owens Lake system.

Shallow Flooding and Ponds

The shallow pools and ponds created by the shallow flooding BACM are the primary driver behind increasing bird populations in Owens Lake (Roberts et al., 2016) (see Figure 3-8). While the remnant brine pool is too saline to support the highly productive food web typical of alkaline lakes, the low- to moderate-salinity pools created by shallow flooding can support extremely high production of algae, which then support robust populations of brine flies along lake shores (Herbst, 2001). This robust food web is strongly dependent on management of salinity levels and on minimizing accumulation of toxic elements (Herbst, 2001; LADWP, 2010; Pavlik, 2008; Roberts et al., 2016). Since shallow flooding began, brine flies have become the most abundant invertebrate at Owens Lake, and most shallow flooding cells contain at least one of the two dominant brine fly species, *Ephydridae auripes* and *E. hians.* In at least some of the shallow flooding cells, brine shrimp (*Artemia* species) have also been detected (LADWP, 2010). Other diverse saline-tolerant invertebrates have also established in the seasonally moist or saturated areas created by dust control efforts, with densities highest in moderate- to high-salinity ponds (up to approximately 100 g/L salinity [Herbst, 2001; NRC, 1989]), and diversity highest in low-salinity ponds. These high inver-

FIGURE 3-8 Shallow flooding for dust control creates low to moderate salinity pools that provide a robust food web that attracts thousands of birds to Owens Lake.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

tebrate populations, in turn, support high bird populations (LADWP, 2010; Pavlik, 2008; Robinson, 2018; Smith, 2000). Fresh and low-salinity pools also enhance self-recruitment of vegetation, particularly saltgrass and freshwater wetland plants, depending on the salinity (LADWP, 2010). The shallow flooding BACM creates aquatic habitats that are rare in the Owens Valley (Manning, 1992) and throughout the western United States—providing habitat that is critical for conservation at the local, regional, and global scales (Oring et al., 2013; Wilsey et al., 2017).

In addition to the important habitat provided by the watered areas, the engineered "cell" structure of the dust control projects lead to high area of roads and berms that act as shoreline for species such as brine flies and lizards. Dust control features provide three-fold more shoreline habitat than the historic lake shoreline (Robinson, 2018).

Alkali Meadows

Alkali meadows are common at springs and artesian well outfalls, largely on the edges of the lake (see Figure 3-9). They are increasingly prevalent in the Owens Lake bed, through self-establishment in lower-salinity shallow flood areas (see Figure 3-10) and through planting as part of the managed vegetation BACM.

Alkali meadows are state-designated sensitive habitat (Sapphos Environmental, Inc., 2008) and are hotspots of diversity, with more than 60 plant species common in the alkali meadows of the Owens Valley (Pavlik, 2008). In the Owens Lake bed, saltgrass (*Distichlis spicata*) is the most common vegetation type, because of both natural recruitment and use in the managed vegetation BACM (discussed in more detail in Chapter 4).

The composition of alkali meadows depends on the quantity and salinity of the water supply. Freshwater areas are dominated by grasses, rushes, sedges, and herbs, while more alkali areas are dominated by salt grass. Saturated alkali meadows are perennially wet and host the highest plant speciesand structural diversity, thus providing the most diverse habitat for animals. Moist alkali meadows have perennially moist soils, which result in lower plant structural and species diversity. These meadows are often dominated by saltgrass and can also host

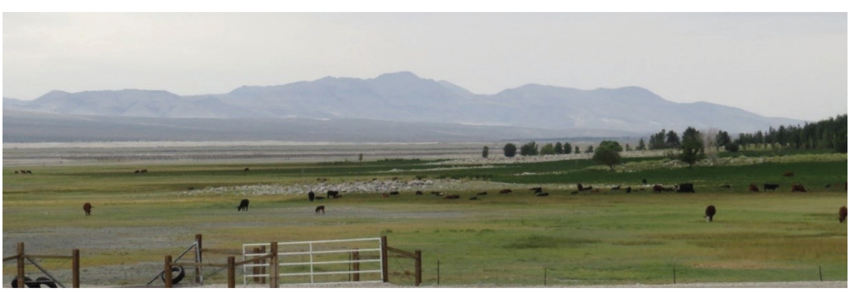


FIGURE 3-9 Alkali meadow along the western edge of Owens Lake.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

FIGURE 3-10 Alkali meadow species self-recruiting into a shallow flooding BACM.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

other wetland species such as alkali pink (*Nitrophila occidentalis*) and yerba mansa (*Anemopsis californica*). When moist meadows are influenced by freshwater springs and seeps, they can also host other species including Baltic rush (*Juncus arcticus* species) and three square (*Schoenoplectus* species). The third type of alkali meadow is dry alkali meadow, which is dominated by saltgrass but can also include Parry's saltbush (*Atriplex parryi*), shadscale (*Atriplex confertifolia*), and alkali pink (*Nitrophila occidentalis*). These three types of alkali meadows are habitat for several plant species with high conservation priority (McLaughlin, 2010) and host a high diversity and density of invertebrates, birds, and small mammals, but are not key habitat for most reptiles (LADWP, 2010).

The managed vegetation BACM (see Chapter 4) has resulted in extensive establishment of saltgrass in playa areas that have been leached of salts (LADWP, 2010). These saltgrass meadows are key habitat for bird species that are distinct from those benefiting from shallow flooding, such as the Savannah sparrow, northern harrier, American kestrel, and horned lark. Other wildlife that benefit from this habitat type include harvester ants, spiders, grasshoppers, kangaroo rats, pocket mice, deer mice, voles, pocket gophers, jack rabbit, and desert cottontail. Tule elk may use these dry alkali meadows for resting, but saltgrass is low-quality forage and therefore unlikely important in their diet. There is some evidence that bobcat, coyotes, kit fox, gray fox, ringtail, and badger use these habitats in Owens Lake. A low diversity and

FIGURE 3-11 Freshwater marsh in the Delta region where the Owens River enters the lakebed.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

population of lizards utilize alkali meadows in Owens Valley, but they have not been detected in managed vegetation areas of Owens Lake (LADWP, 2010).

Other Wetland Habitats

Springs tend to be dominated by freshwater and host diverse drought-susceptible plant species, aquatic bivalves, spring snails, and salamanders, all of which are at risk if the springs disappear due to extensive groundwater use (Pavlik, 2008). Marshes are high-productivity habitats dominated by plants such as reeds, rushes, cattail, and willows, and they support high populations of birds, small mammals, and mussels (Madsen and Kelly, 2008). The Delta (see Figure 3-11), where Owens River enters the lakebed, includes 755 acres of wetland, including marsh and alkali meadow, and a narrow strip of riparian woodland. This area is rich in plant and animal diversity, and it provides an important hotspot of diversity in the landscape, particularly for species relying on perennial sources of water (LADWP, 2010).

Upland Scrub

Various communities of upland scrub systems are common in the Owens Valley and can provide important habitat around the lake (see Figure 3-12) as well as on the lakebed. In general, upland scrub is dominated by widely spaced shrubs, with the species of shrub and the cover of herbaceous vegetation varying by scrub type. Scrub types vary substantially in whether they are dependent on groundwater, and if so, the depth of groundwater that they require (Elmore et al. 2003). Shadscale scrub is not reliant on groundwater (Elmore et al. 2003) and is common in well-drained alluvial fans around Owens Lake, but it can also be found in poorly drained alkaline basins adjacent to riparian areas, meadows, and playa

FIGURE 3-12 Diverse shrublands at lake margins (top) and surrounding the lake (bottom).
SOURCE: Photo courtesy of Valerie Eviner, panel member.

(LADWP, 2010; Smith, 2000). This habitat tends to be dominated by shrubs such as shadscale (*Atriplex confertifolia*) and budsage (*Artemesia spinescens*), but it can also contain winterfat (*Krascheninnikovia lanata*), an important winter forage for wildlife (MHA Environmental Consulting, 1994). Desert saltbush scrub has lower vegetation cover, more bare ground between shrubs, and a seasonal cover of annual plants. It is common in highly saline or alkaline soils, such as in playas (MHA Environmental Consulting, 1994), and is found in areas both with and without shallow groundwater (Elmore et al. 2003). At Owens Lake, greasewood (*Sarcobatus vermiculatus*) and Parry's saltbush (*Atriplex parryi*) dominate this habitat. The desert sink scrub is reliant on groundwater (Elmore et al. 2003) and has lower vegetation cover and biomass compared to the other scrub types. Parry's saltbush dominates this habitat at Owens Lake, but there is also significant cover of greasewood, seepweed, and *Atriplex* species. In Southern Owens Valley on slopes and alluvial vans, creosote bush scrub predominates on well-drained soils with low alkalinity and salinity (Robinson, 2018).

In general, upland scrub provides important habitat for diverse insects, including ants, butterflies, wild bees, beetles, and grasshoppers. Of the Owens Lake habitats, upland scrub provides habitat for the most diverse numbers of lizards and snakes. Upland bird species that are supported include the sage sparrow, loggerhead shrike, and burrowing owl, as well as a number of thrasher species. Mammals include gophers, kangaroo rats, ground squirrels, rabbits, coyote, kit fox, bobcat, and various species of mice (LADWP, 2010). Several shrub species have been added to the managed vegetation BACM, and current studies at Owens Lake are assessing the details of shrub type, structure, and density needed to achieve required dust control (see Chapter 4).

Bird Conservation

Although the California Department of Fish and Wildlife recognizes the conservation importance of the diverse habitats at Owens Lake, habitat goals have almost exclusively focused on birds associated with standing water. The addition of water to the lakebed for dust control created extensive habitat for water birds, as indicated by Audubon's designation of Owens Lake as an Important Bird Area and the Western Hemisphere Shorebird Reserve Network's designation as a site of international importance. Shallow flooding during dust control season (October 16-June 30) has restored the role of Owens Lake as critical habitat for diverse bird species along the Pacific Flyway, with Owens Lake now hosting populations of more than 100,000 birds during the spring and fall migrations. Water coverage that extends into the summer supports summer breeding and provides juvenile habitat. Because of shallow flooding dust control efforts, Owens Lake is now one of the most important breeding sites in California for Snowy Plover, a state species of special concern that breeds from March to July (Oring et al., 2013). Tourism and recreation opportunities at Owens Lake have also been enhanced by the increase in bird populations and the addition of visitor areas and trails.

The habitats provided at Owens Lake have regional to global conservation implications, because migrant shorebirds rely almost exclusively on saline lakes in the Western United States, particularly throughout the Great Basin Desert (in which Owens Lake is located). These saline lakes support greater than 99 percent of North America's population of Eared Grebes, up to 90 percent of Wilson's Phalaropes, and greater than 50 percent of American Avocets, and over the past 150 years, more than half of these lakes have shrunk by 50-95 percent (Wilsey et al., 2017). Since 1973, shorebird populations in the Great Basin region have decreased by 70 percent (Haig et al., 2019). Climate change will exacerbate this trend, leading to many Great Basin water bird species losing at least half of their current range by 2050 (Langham et al., 2015) and experiencing decreased quality of the habitat that remains, because of shorter seasons of water availability and increased salinity in the aquatic habitats (Haig et al., 2019). Although conservation of Mono Lake (approximately 140 miles to the north of Owens Lake) has been critical for bird conservation, Owens Lake provides migratory habitat that is unique from Mono Lake, because its lower elevation (3,600 feet, as compared to 6,378 feet) provides a longer season for migratory birds (California Department of Water Resources, 2004).

As is common in many alkali lakes, high bird populations are supported by extremely high production of algae, which, in turn, supports high populations of brine flies and brine shrimp. Long-term management of salinity levels to support this food chain is critical, because it is common in alkali lakes for salinity to build up over time, which decreases food chain productivity (LADWP, 2010; NRC, 1989).

The Owens Lake Habitat Management Plan lists 114 bird species observed at Owens Lake, including 27 species of shorebirds (LADWP, 2010). The Audubon birder's checklist[4] lists 15 bird species of special concern and a total of 270 bird species recorded in the area of Owens Lake. The diversity of species supported is due to the variety of habitats created by the engineered structure of Owens Lake, with distinct management cells that differ in depth of flooding, salinity, and surrounding habitats (such as the density of vegetation and type of substrate in which to nest) (LADWP, 2010; Robinson, 2018). This heterogeneous landscape supports the unique needs of different bird species, as demonstrated by the five focal guilds of interest: (1) breeding shorebirds, (2) migrating shorebirds, (3) breeding waterfowl, (4) migrating waterfowl, and (5) diving waterbirds. In each of these guilds, the most abundant species tend to be the most salt-tolerant species (Roberts et al., 2016).

The effect of changes in water use at Owens Lake on bird habitats and populations is difficult to quantify. Understanding the wildlife effects of changes in water-based dust control requires quantification of the spatial extent of standing water, the depth of that water, and the seasonality of its application relative to specific bird species that are being managed. A habitat suitability model is currently being used to track changes in potential habitat of the different bird guilds and to aid in long-term landscape-scale planning. A detailed analysis of this approach was conducted by Point Blue Conservation Science (Roberts et al., 2016) and is discussed in Chapter 5 of this report.

[4] See https://ca.audubon.org/conservation/new-opportunities-birds-owens-lake and https://friendsoftheinyo.org/owens-lake-bird-festival-old/bird-checklist-owens-lake (accessed February 4, 2020).

Breeding and migrating shorebirds. In their review of Owens Lake birds, Roberts et al. (2016) highlighted that the breeding shorebird guild should be the highest priority for habitat management because Owens Lake has great potential to provide important breeding habitat for salt-tolerant shorebirds, which is extremely rare in the region. Changes in management of the shallow flooding areas could further enhance the breeding shorebird habitat by extending shallow flooding periods into July and August, thus providing rare habitat for migrating birds at this time of year, extending the breeding season, and providing habitat for juveniles. These pools could also be managed to decrease salinity where it limits invertebrate productivity and shorebird presence (Roberts et al., 2016).

Two important shorebirds, the Snowy Plover and American Avocet, commonly breed in Owens Lake dust control areas and perimeter wetlands, but use distinct habitats (Roberts et al., 2016). The Snowy Plover requires relatively shallow water for feeding (1-2 cm [0.4-0.8 inches] depth) (Roberts et al., 2016). Brine flies are its primary food source, but it can also feed on other invertebrates (LADWP, 2010). In contrast to the Snowy Plover, the American Avocet can feed in relatively deeper water (15-25 cm), feeding on brine flies and brine shrimp. Other species in this guild are unlikely to be breeding in Owens Lake currently (Roberts et al., 2016), but as alkali meadow vegetation becomes more prevalent in the Owens Lake playa, it is expected that suitable habitat for the Long-billed Curlew and Wilson's Phalarope may develop (LADWP, 2010).

The Snowy Plover is a California State bird of special concern and thus is a focus of management on Owens Lake. In addition to its requirements of no net loss of aquatic habitat functions, values, and areas (compared to the 2008 conditions), the California Department of Fish and Wildlife has established specific requirements in perpetuity to protect shorebirds and the Snowy Plover:

- Manage 1,000 acres for shorebirds and Snowy Plovers.
- Maintain a baseline population of 272 Snowy Plovers, including a minimum 523 acres for Snowy Plover habitat (e.g., shallow flooding of 12 inches of water or less, in close proximity to exposed sand or gravel sites for nesting). This requirement is distinct from the 1,000 acres managed for shorebirds in general.

Pools managed for Snowy Plover maintain flooding later into the summer (July 21) compared to the standard shallow flooding BACM (LADWP, 2010).

Migrating shorebirds make up a large population of Owens Lake birds seasonally, with their highest use of the lake occurring during the spring and fall migration seasons. They eat aquatic and terrestrial invertebrates, as well as seeds. The most abundant migrating shorebirds include American Avocet, Western and Least Sandpipers, and Wilson's and Red-necked Phalaropes. They are a diverse guild, with species differing in salinity tolerance and preferences for foraging habitats that range from dry surfaces to deeper ponds. Thus, this guild is particularly difficult to model based on habitat, which is the approach currently used to plan for and track changes in bird habitat at Owens Lake (Roberts et al., 2016).

Breeding and migrating waterfowl. Before the shallow flood BACM was implemented, waterfowl at Owens Lake were restricted to artesian wells and the northern end of the brine pool (where a limited quantity of freshwater enters from the Owens River, as required to sustain the brine pool) (LADWP, 2010). Migratory waterfowl are now abundant in shallow flood areas, with higher population size and diversity in low-salinity cells. This guild rests in vegetated areas, but species vary in the density of vegetation they require. Waterfowl species also vary in food preferences, with geese relying largely on terrestrial vegetation, while dabbling ducks are surface aquatic feeders that can feed on seeds, vegetation, or invertebrates. The dabbling duck species, Northern Shoveler, is the dominant waterfowl at Owens Lake, comprising 72 percent of the waterfowl population annually and 96 percent in the fall migration period. Its dominance is likely because it is one of the few species adapted to sieving out invertebrates from water, and plant-based foods are limited in the lake because of the lack of wetlands, while animal-based food such as alkali flies are abundant in shallow flood BACM areas (Roberts et al., 2016).

Compared to other bird guilds at Owens Lake, breeding waterfowl have much lower abundances. Gadwall is the most common breeding species, and Mallards, Green-winged teal, Cinnamon teal, and Norther pintails are relatively common (Roberts et al., 2016). Roberts et al. (2016) concluded that because breeding waterfowl are generally not salt-tolerant, they were unlikely to be abundant prior to water diversion and, thus, should have the lowest habitat management priority of all of the bird guilds at Owens Lake.

Diving waterbirds. The Eared Grebe and Ruddy Duck are the dominant diving waterbirds at Owens Lake. Owens Lake is not suitable for most other diving waterbirds because they primarily rely on fish as food, and there are no fish in Owens Lake. At Owens Lake, diving waterbirds generally are not found in ponds less than 40 acres in size (Roberts et al., 2016).

Other birds. Beyond the focal bird guilds of interest, diverse other types of birds use Owens Lake as habitat. For example, Grebes feed on brine shrimp, brine flies, and other invertebrates. Ibis are common in areas with emergent or wetland vegetation. Rails are generally common in wetlands, and the American coot frequents shallow flooding areas (LADWP, 2010).

Shallow flooding dust control has significantly increased the presence of gulls from spring through fall, and although they have attempted to nest, whether they have successfully bred at Owens Lake is unknown. Their presence of Owens Lake is a concern because of their potential to disrupt shorebirds such as the Snowy Plover. Similarly, the Common Raven, while relatively rare, is of concern because it can predate on the chicks and eggs of shorebirds, especially Snowy Plover (LADWP 2010).

Challenges to Managing Habitat at Owens Lake

In this arid system, water is the primary creator of habitat, from shrubs supported by rainfall and shallow groundwater to alkali meadows near surface seeps to avian habitats in shallow ponded areas. Decreasing water use for dust control will decrease shallow flooding and pond areas and will compromise current habitat (LADWP, 2010). Although the current management configuration provides critical habitat, Point Blue's review of birds at Owens Lake highlights that the infrastructure and landscape design can be improved to maintain bird habitat under the pressure of decreasing water use (Roberts et al., 2016). Habitat for plants and wildlife can also be improved through the managed vegetation BACM, with the expansion of dry alkali meadows and upland scrub, which when mature, have relatively lower water requirements while controlling dust. Roberts et al. (2016) note the pressing need for innovative trials that manage for habitat with lower water use.

Another challenge is to ensure that future water management decisions related to providing dust control on Owens Lake do not compromise important habitats in the landscape beyond the lake. For example, groundwater pumping and water diversion can disrupt seeps, springs, streams, and rivers, compromising key perennially wet habitats (e.g., marshes, meadows, riparian areas) that are a hotspot for diversity in the landscape and are relatively rare in the region (Libecap, 2007; Manning, 1992; Pavlik, 2008; Smith, 2000). Lowering of the water table through water diversion and groundwater pumping can also decrease the density of shrubs (Elmore et al., 2006; Pavlik, 2008) and decreases the resilience of vegetation communities during droughts (Elmore et al., 2003).

MINERAL RESOURCES

Owens Lake has a long mineral and mining history, beginning during Spanish ownership with silver mining at Cerro Gordo (east of Keeler; see Figure 1-2) and continuing today. Sodium carbonate (common name soda ash) was first mined in 1887 near Keeler using solar evaporation of Owens Lake waters. The desiccation of Owens Lake by 1926 led to formation of a sodium rich brine, and the precipitation of sodium sulfate and sodium carbonate production both from brines and surface salts continued through the 20th century by several companies at several locations, but primarily along the western portion of the lake, where the original lake was deepest (Ver Planck, 1959).

Ore deposits of trona (a salt consisting of sodium carbonate and sodium bicarbonate) are estimated at approximately 70 million tons. Mining is conducted by removing the 2- to 5-foot thick salt crust by excavator and drying the salt before final shipping. Since 2006, Rio Tinto Minerals has operated the mining operations on Owens Lake, with a mineral lease of approximately 24 square miles across the western portion of the lakebed (Lamos, 2013).

The mineral lease area is not considered to be a dust producing area and is not covered in the 2016 SIP (GBUAPCD, 2016a). Although the 2008 Environmental Impact Statement (GBUAPD, 2008) found no significant impact of dust control on mining, LADWP is not allowed to infringe or impact mineral lease areas, either through dust mitigation or releases from the Owens River. Because the deposit consists of evaporite minerals and a sodium-carbonate-rich brine, they are sensitive to flooding or dilution from excess water inflows, potentially from flash floods or by surface drainage or enhanced groundwater flows from the dust control areas. As indicated in GBUAPCD (2008), surface drainage on the lakebed is expected to be managed carefully so that mining operations are not affected. During the 2017 runoff season, LAWDP warned that uncontrolled releases of water down the Owens River could impact mining operations. Although releases were controlled and no impact occurred, this event underscores potential tradeoffs in future flood management decisions between adverse impacts to existing mineral leases or to dust control areas.

The presence of dust-limiting brines and salt crusts in the western portion of the lakebed also highlights the potential for synergies between mining and dust control. The development of the brine BACM with shallow flooding backup (see Chapter 4) is partially a result of the observation of stable salt ponds and salt crusts in the western portion of the lakebed. Brines produced as byproducts of managed vegetation or soil leaching in dust control areas could potentially represent a replenishment of trona-rich brines to the leases.

CONCLUSIONS AND RECOMMENDATIONS

Effects of Climate Change on Water Availability

Conclusion: Climate change is anticipated to adversely impact the Owens Valley water supply, with longer and more severe droughts and more extreme wet years. As a result of climate-related changes, availability of water for dust mitigation will be more variable, more water will be needed during dry periods to mitigate dust and maintain habitat, and more pressure will be put on the system to support downstream water demands.

Cultural Resources

Conclusion: Local Native American tribes are an integral part of the ecosystem and have a strong sense of ownership and stewardship of land in the Owens Valley. The tribes have requested that culturally and historically significant sites not be subjected to heavy machinery and leveling operations inherent with DCM construction. Tribal concerns extend beyond areas containing artifacts to include the natural landscape, because many topographic features and ecosystem types are highly valued.

Habitat Resources

Conclusion: The value of diverse, aquatic and non-aquatic habitats and the relative abundance of those habitats in the Owens Valley are important considerations in setting priorities for lake-wide management decisions.

Conclusion: Water additions to Owens Lake provide valuable and often rare habitat, both locally and regionally—including one of the best breeding habitats in California for a species of special concern, the Snowy Plover, and saline aquatic habitat that is regionally rare and critical for migratory birds at the regional and global scales. Decreases in water use for dust control are likely to compromise habitat.

Recommendation: Prioritization of conservation targets should focus on the regionally rare habitats that Owens Lake can provide, and the species most suitable to those habitats.

Recommendation: The most valuable, diverse, and rare habitats in the region (e.g., wetlands, riparian systems) are those most vulnerable to groundwater pumping and water diversions. Therefore, management of Owens Lake should not disrupt water sources to these habitats.

Mineral Resources

Conclusion: The western portion of the lakebed, including mineral leases covering a large portion of this area, are hydraulically connected to the current dust control areas as well as the Owens River. In particular, excess flooding from the Owens River could lead to tradeoff decisions between impacts on dust control areas and impacts on mineral mining operations.

4

Evaluations of Dust Control Measures

The panel was tasked with assessing the performance of alternative dust control measures (DCMs) in reducing particulate matter 10 micrometers or less in aerodynamic diameter (PM_{10}) at the Owens Lake bed under reduced water use. The panel was also tasked with "consider[ing] associated energy, environmental and economic impacts, and assess[ing] the durability and reliability of such control methods."

The panel identified nine promising DCMs that are not currently considered Best Available Control Measures (BACMs). This includes natural solid and porous artificial roughness, engineered solid and porous artificial roughness, cobbles, sand fences, and solar panels, as well as two proposed modifications of current BACMs (precision surface wetting and shrubs with modified percent vegetative cover). To provide a basis for comparing the performance of these DCMs, the panel also evaluated the three current approved BACMs and three additional BACM modifications using the same criteria.

In the sections on each DCM below, the panel discusses dust control performance; practical considerations, including durability and time to achieve full performance; water use; and environmental implications, including habitat provided, aesthetic considerations, and potential effects of infrastructure installation or maintenance on environmentally sensitive areas. However, the panel did not presume an understanding of the many factors that influence the acceptability of a DCM on environmentally sensitive areas. The panel also discusses energy use; cost; systemwide factors, such as synergies with other measures and sustainability concerns; and information gaps. Table 4-1 provides an overarching summary of the evaluations discussed in this chapter.

EXISTING BACMs

Three BACMs have been approved for the Owens Lake bed: shallow flooding, gravel, and managed vegetation. Three modifications to the shallow flooding BACM are also discussed in this section: dynamic water management, brine with shallow flooding backup, and tillage with shallow flooding backup.

TABLE 4-1 Synthesis of the Evaluations of BACMs and Alternative Dust Control Measures

Dust Control Measure (with area as of April 2019)	Reported Control Efficiency (%)	Initial and Long-term Water Use (ft/yr)	Capital Cost ($/mi²) and Lifespan	Operating Cost ($/mi²·yr)	Environment: Habitat Value	Environment: Impact to Cultural Resources	Time to Full Performance	Site Suitability
APPROVED BACMs								
Shallow Flooding BACM: Shallow Flooding (19 mi²)[a]	99%	2.7–3.2	$26–32 M; 20- to 30-yr life	$0.28–0.34 M	High value; regionally rare	High land disturbance	Immediate	Avoid sites next to drained managed vegetation
Shallow Flooding BACM: Dynamic Water Management (10.5 mi²)	99%	2.6	~$26–32 M; 20- to 30-yr life	$0.28–0.34 M	High value; regionally rare	High land disturbance	Immediate	Avoid sites next to drained managed vegetation
Shallow Flooding BACM: Brine with Shallow Flooding Backup (3.8 mi²)	99%	0 (but requires backup)	$24 M; 20-yr life	$0.23 M	Low value	High land disturbance	Months to 1 year	Most suitable in low elevations
Shallow Flooding BACM: Tillage with BACM Backup (2.7 mi²)	99%	Initial: ND Long-term.: 0 (but requires backup)	$0.50 M; 5-yr life	$0.42 M	Low value	High land disturbance	Immediate	Most suitable in areas with clay-rich soils
Managed Vegetation (5.4 mi²)	99%	Leach: 0.1–8 1st 2 yrs: 1.2–4 Long-term: 1.1–2.6	$20–36 M; 20-yr life	$1.6–2.4 M	High value; regionally occasional	High land disturbance	2–3 yrs after planting	Most suitable in soils with low salinity and deeper groundwater
Gravel (5.4 mi²)	100%	0	$37 M; 20-yr life	$0.23 M	Low value	High land disturbance	Immediate	Avoid sites adjacent to emissive surfaces

OTHER DCMs								
Precision Surface Wetting	99% attained in testing	Uncertain	ND (~<$32 M); 20-yr life	~$0.32 M	Low to High; regionally occasional	High land disturbance	Immediate	Avoid sites next to drained managed vegetation
Artificial Roughness: Solid Natural	Depends on density and geometry; 92% obs. at Keeler Dune	0 (without plants) Initial: 0.1 w/ plants	~$9–52 M (w/o or w/ plants); lifespan unknown	~low to $1.3 M (w/o or w/ plants)	Moderate; regionally abundant	Potentially low land disturbance	Immediate	Suitable to all locations
Artificial Roughness: Solid Engineered	Depends on density and geometry; 90% observed in field test	0	~$45 M; lifespan unknown	ND; expected to be low	Moderate; regionally abundant	Potentially low land disturbance	Immediate	Suitable to all locations
Artificial Roughness: Porous Natural	Unknown; dependent on density and geometry	0	ND; lifespan unknown	ND	Moderate; regionally abundant	Potentially low land disturbance	Immediate	Suitable to all locations
Artificial Roughness: Porous Engineered	Unknown; dependent on density and geometry	0	~$64 M; lifespan unknown	ND; expected to be low	Moderate; regionally abundant	Potentially low land disturbance	Immediate	Suitable to all locations
Shrubs (with modified % cover)	Depends on density	Leach: 0.1–8 Initial: ≥ 0.2 Long-term: ~0	ND	ND; expected to be low	Moderate; regionally abundant	Potentially low land disturbance	5–10 yrs	Most suitable in soils with low salinity and deeper groundwater

continued

TABLE 4-1 Continued

Dust Control Measure (with area as of April 2019)	Reported Control Efficiency (%)	Initial and Long-term Water Use (ft/yr)	Capital Cost ($/mi^2) and Lifespan	Operating Cost ($/mi^2·yr)	Environment: Habitat Value	Environment: Impact to Cultural Resources	Time to Full Performance	Site Suitability
Cobbles	Unknown; estimated at 100%	0	ND	ND; expected to be low	Low to Moderate; regionally abundant	High land disturbance	Immediate	Avoid sites adjacent to emissive surfaces
Sand Fences (0.4 mi^2 as min. dust control)	70–90%; dependent on fence spacing and geometry	0	$15 M; 5-yr life	$0.6 M	Low	High land disturbance	Immediate	Suitable to minimum dust control areas
Solar Panels	Likely > 99% on gravel; untested on non-gravel.	Initial: ~1 Long-term: ~0.02	~$80–120 M, not including gravel; 25- to 40-yr life	ND	Low; potential adverse impacts	High land disturbance	Immediate	If gravel used, avoid sites adjacent to emissive surfaces

NOTES: ND = No data; M = millions. Habitat value ratings represent the panel's subjective assessment, based on descriptions in Chapter 3 of the diversity and productivity of the habitat in terms of food web productivity/ability to support wildlife. Habitat abundance rating is modeled after the Braun-Blanquet cover class method for vegetation cover (Braun-Blanquet et al., 1932), which classifies cover as rare (<5%), occasional (5–25%), common (25–50%), abundant (50–75%), and dominant (75–100%), with Owens Valley percent cover of these habitats classified by data from Manning (1992).

[a] Shallow flooding area including dynamic water management was reported by Logan (2019a) as 29.7 square miles (see Table 1-1). Shallow flooding area without dynamic water management reported here as the total minus the area of dynamic water management in the 2019 water year, although these operations can vary from year to year.

SOURCE: Data on costs and water use for current BACMs from Valenzuela (2019b; 2020) and Logan (2019a). Performance data and cost and water use estimates for non-BACMs are referenced or explained in the chapter discussions.

FIGURE 4-1 Dust control at Owens Lake using the shallow flooding BACM also provides habitat for many different bird species.
SOURCE: Photo courtesy of David Allen, panel member.

Shallow Flooding

Shallow flooding is the most widely used BACM at Owens Lake (see Figure 1-4 and Table 1-1). Water is spread across a graded surface with a minimum of 72-75 percent (depending on the dust control area) of the surface covered with standing water or surface-saturated conditions during the peak dust season between mid-October and mid-May (see Figure 4-1). A variety of different water delivery systems are used for this BACM, including water supply through lateral pipes and distributed sprinklers. The presence of standing water completely eliminates dust generation from the wetted surface and also traps blowing sand that enters the ponded area.

Performance

Evaluation of the performance of shallow flooding for dust control is based primarily on data from Hardebeck et al. (1996) in which shallow flooding designs were tested at the northern end of the lakebed on primarily sandy soils. Sand flux samplers and PM_{10} monitors were used to estimate differences in dust emissions associated with wetted surfaces, using natural storm conditions and wind tunnel testing. The control efficiency showed a strong correlation with the percentage of area covered by water (Hardebeck et al., 1996). Although there was scatter in the results, extrapolation of those data revealed that at water coverages greater than 75 percent of the dust control area, control efficiencies of 99 percent or greater for PM_{10} can be obtained (see Figure 4-2a). For the 16.5 square miles of shallow flooding implemented by 2003 with minimum flooded coverage of 75 percent, the Great Basin Unified Air Pollution Control District (District) estimated an average control efficiency of 99.8 percent in 2004 based on sand flux as a surrogate measure for PM_{10} (GBUAPCD, 2008).

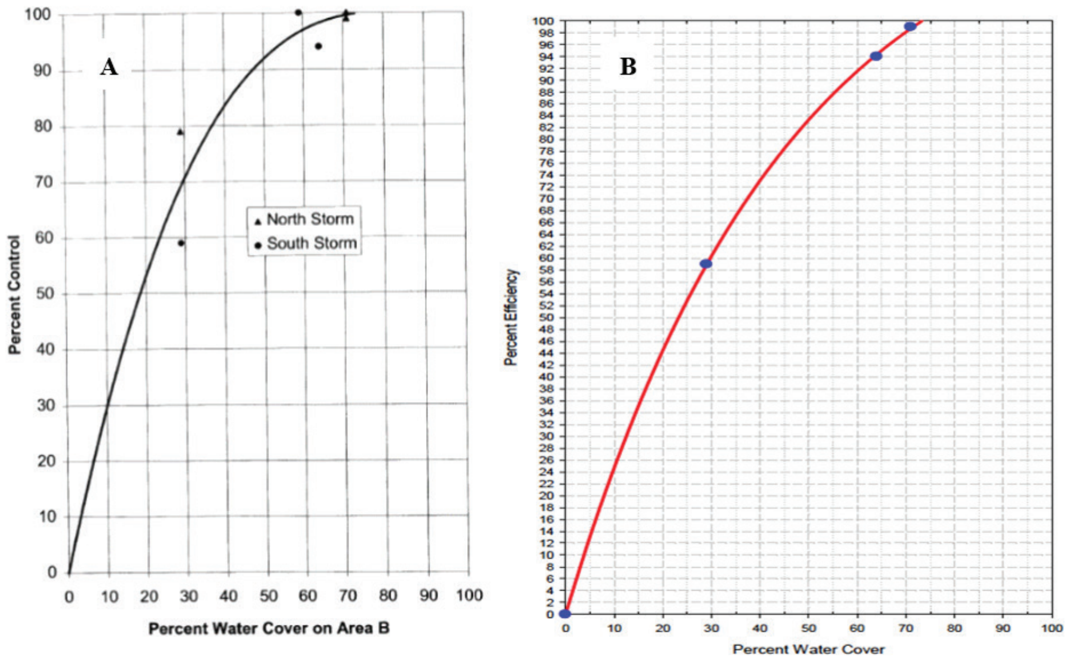


FIGURE 4-2 (A) Original shallow flooding field data (solid circles and triangles) and fitted curve documenting control efficiency (based on both PM_{10} and sand flux measurements) as a function of shallow flooding coverage, from which the 75 percent wetted criteria was determined. (B) Shallow Flood Control Efficiency Curve from the 2008 State Implementation Plan (SIP) demonstrating 99 percent control efficiency at 72 percent or greater wetted cover was developed through subsequent research.
SOURCES: Hardebeck et al. (1996) and GBUAPCD (2008).

The 2008 State Implementation Plan (SIP) (GBUAPCD, 2008) included a modified Shallow Flood Control Efficiency Curve (see Figure 4-2b), fitted to three of the original data points. This curve is currently applied to shallow flooding areas within the 2006 Dust Control Area (12.7 square miles), with 72 percent flooded coverage assumed to provide 99 percent PM_{10} control efficiency. Current efforts are underway to refine the degree of wetness required for 99 percent control efficiency (e.g., Bannister et al., 2016).

The District Governing Board requires that surface flooding conditions be met from October 16 to June 30, reflecting the period with the most intense wind and surface emissivity conditions during the dust season. The percentage of standing water coverage may be decreased to 70 percent from May 16 to May 31, 65 percent from June 1 to June 15, and 60 percent from June 15 to June 30 (see Table 4-2) (Board Order 160413-01).[1]

[1] District Governing Board Order #160413-01 Requiring the City of Los Angeles to Undertake Measures to Control PM_{10} Emissions from the Dried Bed of Owens Lake. See https://gbuapcd.org/Docs/District/AirQualityPlans/OwensValley/Board_Order_FINAL_20160425.pdf (accessed January 28, 2020).

TABLE 4-2 Examples of Owens Lake BACM Performance Criteria

	BACM		Performance Criteria
Shallow Flooding BACM	Shallow Flooding	% wetness	75% or 72% wetness from Oct 16–May 15; In 99% CE, spring ramping allows decreases: May 16–31 = 70%; June 1–15 = 65%; June 16–30 = 60%[a,b]
	Dynamic Water Management	Sand Flux	>5.0 g/cm²/day = reflood threshold[a,b]
		IPET	Mitigation required/reflood when visible dust emissions occur when operated at reference test height[a,b]
		Dust Plume Obs.	Dust observations by human observers or remotely using video or photos[a]
	Brine with Flooding Backup	Sand Flux	>5.0 g/cm²/day = reflood threshold[a,b]
		Surface cover	Required 75% or 72% total surface cover (depending on dust control area) of a mix of stable qualifying surfaces: 1. Standing water or hydrologically saturated surface, 2. Evaporite salt deposit with a minimum thickness of 1.5 cm, and 3. Capillary crust with a min thickness of 10 cm and <1/3 of minimum required total cover (24% or 25%) Reflood when <60%; Maintenance required if >60% but less than required or >1/3 capillary[a,b]
		IPET	Mitigation required/reflood when visible dust emissions occur when operated at reference test height[a,b]
		Dust Plume Obs.	Dust observations by human observers or remotely using video or photos[a]
	Tillage with Flooding Backup	Sand Flux	>1.0 g/cm²/day = reflood threshold; >0.5 g/cm²/day = maintenance[b,c]
		Tillage Roughness	Average ridge spacing/ridge height (RS/RH) in 40-acre blocks should be <10; RS/RH >12 = reflood threshold, RS/RH of 10.1–12 = maintenance[b,c]
		Ridge Height	Average ridge height (RH) <1.0 ft = reflood threshold, RH <1.3ft = maintenance[b,c]
		PM_{10} Monitoring	Upwind-downwind concentration difference >100 µg/m³ = reflood threshold, >50 µg/m³ = maintenance
		Surface Armoring	>60% clod cover and clods + 1/2" diameter[b,c]
		IPET	Mitigation action required/reflood threshold = visible dust emissions when operated at reference test height[b,c]

continued

TABLE 4-2 Continued

BACM		Performance Criteria
Managed Vegetation	% Cover	37% overall average vegetation cover of locally adapted native species.[a]
Gravel	Cover	100% coverage of either 4" thick gravel with size screened to >½ inch in diameter, or 2" thick gravel with size screened to ½ inch in diameter underlain w/ geotextile fabric[a,b]

NOTE: CE = control efficiency; IPET = Induced Particle Emissions Test.

[a] District Governing Board Order #160413-01 Requiring the City of Los Angeles to Undertake Measures to Control PM_{10} Emissions from the Dried Bed of Owens Lake. See https://gbuapcd.org/Docs/District/AirQualityPlans/OwensValley/Board_Order_FINAL_20160425.pdf (accessed January 28, 2020).

[b] District Rule 433, Control of Particulate Emissions At Owens Lake, adopted March 13, 2016. See https://ww3.arb.ca.gov/drdb/gbu/curhtml/r433.pdf (accessed January 28, 2020).

[c] Stipulated Judgment in the matter of the City of Los Angeles v. the California Air Resources Board et al. Superior Court of the State of California, County of Sacramento. Case No. 34-2013-80001451-CU-WM-GDS. Approved by the court on December 30, 2014. See https://gbuapcd.org/Docs/District/AirQualityPlans/SIP_Archive/2014_Stipulated_Judgment_20141230.pdf (accessed January 28, 2020).

SOURCE: Logan, 2019d.

These performance criteria are monitored via satellite remote sensing (previously using Landsat 7/8 every 8 days and currently with Sentinel-2 every 5 days).

Practical Considerations

The shallow flooding BACM can achieve full performance following construction and upon reaching the required surface wetness coverage. However, shallow flooding is not appropriate as an emergency measure unless the area has been graded and water distribution infrastructure is present. The BACM itself is quite reliable based on reported results, but it does depend on the reliable supply and the long-term availability of water from the Los Angeles Aqueduct. If water resources are insufficient for shallow flooding, groundwater supplementation can be used, but local groundwater pumping can impact marginal springs and lake shore habitat as demonstrated in similar saline lake systems (Guteirrez et al., 2018; Ortiz et al., 2014). Additionally, changes in salinity in the shallow flooded areas are likely to impact the biota that depend on those systems (see Chapter 3). The shallow flooding BACM also relies on the lake's water distribution system, although it can tolerate short-term interruptions if necessary.

Significant construction, including land leveling and water distribution infrastructure, is required for the BACM. Its lifespan is likely limited by the lifespan of the piping and water distribution hardware, which likely ranges from 20 to 30 years (Valenzuela, 2019b). The BACM is generally durable, however the requirement that the land surface be level to maintain even depths of standing water can be disrupted by sediment-laden flash floods, particularly in the south and east of the lake, which might necessitate regrading and repair to the water conveyance infrastructure.

Water Use

The water use of the BACM is significant, with estimated freshwater consumption of 3.15 ft/year for ponded areas, 2.68 ft/year for sprinkler irrigation, and 3 ft/year for flooding using piped laterals (Valenzuela, 2019b). The cessation of flooding in the summer months does reduce the water demand to well below the annual reference evapotranspiriation (ET_0); using 2018 and 2019 data, the ET_0 is ~6.6 ft/year (2020 mm/year; based on the Food and Agricultural Organization-56 method for estimating crop evaporation [Allen et al., 2005]). Shallow flooding will have greater water demands under a warming climate, because open water evaporation will increase ~3.5 percent for a projected 2°C average warming in the Owens Valley, assuming no change in relative humidity, solar radiation, or mean wind speed.[2]

[2] Estimates of increase in reference or open water evaporation were calculated using FAO's ET_0 Version 3.2 under the assumption of only warming, with all other climate variables remaining unchanged from the 2018-2019 calculation period.

Environmental Implications

The presence of ponded water has significantly increased the avian habitat of the lakebed (see Figure 4-1). Owens Lake is considered by the Audubon Society to be an Important Bird Area and in 2018 was designated a Western Hemisphere Shorebird Reserve Network Site of International Importance. The shallow flooded areas have robust food webs and host a large number of birds (largely migratory, but some breeding), providing critical habitat along the Pacific flyway (Roberts et al., 2016; see Chapter 3). Current heterogeneity in the flooded areas provides habitat for diverse bird species. Specific characteristics of pools, such as salinity, water depth, and surrounding habitat conditions, determine to what extent they support the presence and breeding of waterfowl and shorebirds and the presence of diving waterbirds (LADWP, 2010; Roberts et al., 2016; Robinson, 2018).

Salinity is a major factor affecting the food web (Roberts et al., 2016). Invertebrate diversity is highest in low-salinity pools; electrical conductivity of 25-100 millisiemens per centimeter (mS/cm; approximately 20-100 g/L salinity) results in the highest density of invertebrates and production of benthic algae (Herbst, 2001; NRC, 1989). At more than 120 g/L salinity, the food web will begin to decline and will be decimated by 150 g/L salinity (NRC, 1987). Maintaining low- to moderate-salinity pools can be challenging in a terminal alkali lake, where salinity necessarily accumulates over time, which would lead to a decrease in brine flies that are critical food for birds (LADWP, 2010). Additional water in the summer periods is effective at slowing the buildup of salinity, increasing brine shrimp, and improving breeding habitat for birds (Roberts et al., 2016).

The flooded areas also appear to be of high aesthetic value; for example, these areas feature prominently in the public access points and interpretive centers. Because of the land disturbance associated with surface leveling (to improve water spreading efficiency and minimize water needed to cover the surface) and the amount of infrastructure required, the shallow flooding BACM is not conducive to use on environmentally sensitive areas of the lake.

Energy Use

Energy use during operation of the shallow flooding BACM is relatively low because most shallow flooding is conducted using gravity-fed systems from the Los Angeles Aqueduct.

Cost

The cost of the shallow flooding BACM is significant both in capital costs (surface grading and water distribution system construction) and operating cost (distribution system maintenance and water consumption). The cost of construction, including the water distribution system, ranges from $26 million to $32 million/square mile, depending on the type of water distribution system used. Operating costs are estimated to be between $280,000 and $340,000/square mile, excluding the value of water used from the aqueduct

(Valenzuela, 2019b). As the water rights owner for the supplies of the Los Angeles Aqueduct, the Los Angeles Department of Water and Power (LADWP) does not purchase the water used for dust control, unless water supplies in the Owens Valley fall short of that required amount. Nevertheless, assuming a market value ~$1,000/acre-ft and an annual water use for dust control at Owens Lake of 65,000 acre-ft (largely for shallow flooding), the water use for shallow flooding represents an approximate annual value of ~$65 million/year if such supplies could be allocated to other users.[3]

Systemwide Issues

Under a warming climate, the shallow flooding BACM will consume more water through evaporation. Warming is also expected to reduce the snowpack in the Owens River catchment. Because the Sierra snowpack serves as the major storage reservoir of the system, reduction in the available storage would lead to higher Owens River flows earlier in the runoff season when downstream demand is not yet at its peak. Therefore, climate change may affect the availability of water for the shallow flooding BACM and the potential for flood damage of the infrastructure needed for this BACM.

Information Needs to Inform Decision Making

Long-term potential changes in soil and groundwater salinity as a result of shallow flooding and their propensity to affect dust production are poorly understood. Shallow flooding may, in some areas, leach soluble salts toward the center of the lake (thus reducing the dust potential), change the chemical composition of the near surface salts, or, because of evaporation, actually accumulate additional salts at the surface. Changes in salinity could have a major effect on the food web for shorebirds, and therefore additional information on the capacity to maintain target salinities over time is needed.

In addition, more work is needed to understand the linkage between shallow flooding acreage, depth, salinity, food web production, and bird population sizes. For example, brine flies (and brine shrimp, to a lesser extent at Owens Lake) are the primary food source for most birds at Owens Lake. Brine flies have very patchy spatial distributions in saline lakes (NRC 1987), and understanding of these controls will inform design of shallow flooding strategies that maintain bird populations with reduced water use. The current habitat guild model and monitoring coarsely address the driving mechanisms that control bird presence or populations (e.g., food webs, habitat patch size [which may include multiple dust control areas that provide similar habitat], and adjacency), which limits its effectiveness for projecting the effects of different management scenarios.

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[3] For comparison, rates for purchasing water from the Metropolitan Water District were $1,095/acre-ft in 2019 (Valenzuela, 2020b).

If shallow flooding is to be combined with other DCMs in hybrid control measures, additional information on the control effectiveness of this DCM at areal coverages less than 75 percent is needed.

Shallow Flooding: Dynamic Water Management

Dynamic water management is an operational modification of the shallow flooding BACM that allows for later start dates and/or earlier end dates to reduce water use in areas with historically low PM_{10} emissions.[4] Areas under dynamic water management are carefully monitored, and reflooding is required when specific performance criteria are exceeded (e.g., sand flux greater than 5 g/cm^2 day, visible dust observations, or visible dust emissions when induced particle emission testing[5] is performed at the reference test height). Dynamic water management was approved in 2014 during an extended drought to provide LADWP with flexibility to reduce water use on 13.15 square miles. Operationally, it is used on areas that are already constructed for shallow flooding, and therefore the capital costs are assumed to be mostly identical to that of the shallow flooding BACM. No operating costs were provided. Monitoring requirements are greater than those for the shallow flooding BACM, but other operating costs may be reduced when the area is not flooded.

Water Use

Dynamic water management reduces the volume of water needed for dust mitigation and also provides some flexibility in operations at both the beginning and end of the dust control season. Water savings (compared to the shallow flooding BACM) depend on the start and end dates. In 2018 and 2019, LADWP reported an average water use of 2.6 ft over the areas in which dynamic water management was applied, which is slightly less than the reported water use of 2.7-3.2 ft for the shallow flooding BACM. LADWP reports that, on average, dynamic water management reduced water use at Owens Lake by 1,750 acre-ft/year (Valenzuela, 2019b).

Information Needs to Inform Decision Making

Shorter flooding periods will decrease the potential breeding season for some of the birds and may also disrupt the robust food web on which migrating and breeding birds depend.

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[4] Dynamic water management start dates are established by Board Order 160413-01 Attachment F, while end dates depend on the type of shallow flood system in place. For surface flooded areas, flooding may cease on April 30, with no ramp down requirements as found in the traditional shallow flooding BACM. For areas of sprinkler flooding, surface wetness must be met 2 weeks prior to the start date of dynamic water management, and may be shut off with no ramping period on May 31.

[5] An induced particle emission test involves the use of a small remote-controlled drone (i.e., helicopter-type craft) to generate wind at the surface. The craft is tested in advance to determine the reference height that creates target wind speed of 11.3 m/s measured at 1 cm above the land surface (District Rule 433, Control of Particulate Emissions At Owens Lake, adopted March 13, 2016. See https://ww3.arb.ca.gov/drdb/gbu/curhtml/r433.pdf [accessed January 28, 2020]).

For example, brine shrimp are particularly abundant with warm season flooding (NRC, 1987). Before dynamic water management is more widely adopted at Owens Lake, it would be important to understand the potential habitat effects.

Brine with Shallow Flooding BACM Backup

Owens Lake brines are typically considered an alkaline sodium carbonate-sulfate-chloride brine, following the model of Hardie and Eungster in which sodium is the dominant cation (Friedman et al., 1997). Chemical weathering of the Sierra batholith (primarily from feldspars; Pretti and Stewart, 2002) followed by evaporation lead to an alkaline brine that has been extensively mined for soda ash. The mineralogy of the evaporate minerals formed during evaporative enrichment (at concentrations approaching 450,000 mg/L [Groeneveld et al., 2010]) is complex, and in particular, the phase and mineralogy of sodium carbonate and sodium sulfate salts are strongly influenced by temperature. Their order of crystallization and state of hydration change seasonally, and therefore development of a long-term and stable surface crust at Owens Lake has proven challenging (GBUAPCD, 2016a). Beginning in 2012, a series of tests demonstrated that effective dust control could be maintained by a combination of both wetness (similar to shallow flooding but with a brine solution) and development of thick salt crust. The technique, known as brine with BACM backup, uses brine or salts to cover the surface, with shallow flooding required only when the surface condition deteriorates to a potentially emissive state (at the coverage defined in the previous section) (GBUAPCD, 2016b).

The brine BACM consists of three dust-mitigating surfaces: brine, evaporite salt deposit, and capillary brine salt crust. The liquid brine serves in the same manner as the shallow flooding BACM, eliminating any sand or dust sources as well as capturing saltating particles. The evaporite crust that forms subaqueously from evaporation of standing brine, serves as the armoring of the surface to reduce dust emissions. This crust is primarily evaporite minerals (solid phase salts as well as the potential for interstitial brines) and is not easily eroded by wind. Capillary brine crust, termed from its formation during the capillary rise of shallow brine in the sediments, forms from evaporation of shallow groundwater, precipitating salts both within and on top of the lake sediments (GBUAPCD, 2016b).

The brine with BACM backup (GPUAPCD, 2016b) is required to provide 75 or 72 percent coverage, depending on the dust control area, through a mixture of qualifying surfaces:

- standing water or saturated soils,
- an evaporite salt deposit of at least 1.5 cm thickness, or
- capillary crust of at least 10 cm thickness (at no more than 24-25 percent of the dust control area) (see Figure 4-3).

FIGURE 4-3 Evaporite salt deposits underlain by thick capillary crusts have been shown to prevent PM_{10} emissions.
SOURCE: Photo courtesy of David Allen, panel member.

For areas controlled with brine with BACM backup, reflooding is required when sand flux estimates exceed 5 g/cm^2 day.

The dust control performance has been documented visually, by comparison to the existing brine pool behavior, which is deemed not to be PM_{10} emissive, and by sand monitoring, although typically these areas do not contain appreciable sand-size fraction material. The District reported that no visible dust plumes originated from brine BACM between 2012 and 2015, during a multiyear drought. Until more data are collected during a broader range of precipitation conditions, shallow flooding backup continues to be required for the brine BACM because salt mineral crusts can generate emissive salts as they transition between hydrated and dehydrated states (GBUAPCD, 2016b).

Performance

The durability of the surface is variable, with evaporite crust being quite durable and apparently not subject to significant phase changes. In contrast, capillary crust areas are prone to thermal effects and could become emissive following winter rains or snow events. It remains unclear how durable the evaporite crust is if brine is diverted elsewhere (i.e., is it necessary to keep brine directly beneath the salt crust?). Having the backup of surface wetting significantly improves the reliability of this BACM.

Practical Considerations

The BACM likely achieves full performance quickly because weeks to no more than a few months are needed to precipitate a centimeter of crust. For brines that are far below saturation, full performance may take longer but can easily be calculated from potential evaporation rates and brine salinity. The BACM appears to function well in both sandy and clay soil types, although the measure does require surface grading. The BACM would not be appropriate for use *upgradient* of any BACM that is sensitive to salinity, such as managed vegetation. This BACM is well suited for co-location with any BACM that generates brine or high-salinity waters, such as vegetated surfaces and at the downstream end of shallow flooding where tailwaters can be gathered that are likely high in salinity.

Water Use

The technique has several advantages, including reduced freshwater requirements and the ability to dispose of brines from adjacent tile-drained vegetative BACM sites. The BACM uses no freshwater during construction and, in theory, during operation. However, a source of water for flooding, such as tailwater from a shallow flooding cell, must be available if the surface becomes emissive and the shallow flooding BACM backup is required.

Environmental Implications

The brine BACM provides habitat for brine-loving bacteria and unicellular algae (Armstrong, 1981). The habitat value of the brine BACM alone is low, because salinities of around 100-120 mS/cm can limit invertebrate productivity (Herbst 2001; NRC, 1987), and brine flies can be eliminated above 150 mS/cm (Herbst, 1997; NRC, 1987). However, aquatic ecosystems can be quite productive at the interfaces between brine and freshwater-flooded areas, because the dominant invertebrate species, brine flies, have maximum productivity at 25-100mS/cm (LADWP, 2010). For example, waterfowl populations at Owens Lake have historically been supported in areas of the brine pool that are adjacent to springs or artesian wells (LADWP, 2010). Therefore, this BACM could enhance the feeding habitat for avian species if managed in conjunction with freshwater areas, although saltwater intrusion into these rare freshwater areas must be avoided. Brine BACM sites also provide sinks for salts in this alkaline basin, which helps to maintain lower-salinity habitats throughout the rest of the lake (LADWP, 2010).

Because of the infrastructure and grading required, this BACM is unlikely to be appropriate for environmentally sensitive areas. Reactions to the aesthetics of the brine BACM can

FIGURE 4-4 Dust control using the brine BACM.
NOTE: Dark red to pink brine is bordered by white evaporate crust.
SOURCE: Photo courtesy of Stephanie Johnson, National Academies.

be mixed. Some may see the color of the halophilic bacteria as alien to the landscape, while others may appreciate the seasonal changes in the brine color as an indicator of a living landscape (see Figure 4-4).

Cost

The construction cost of the brine BACM with shallow flooding backup is $24 million/square mile, which is lower than the shallow flooding BACM. Operating costs are $230,000/square mile/year (Valenzuela, 2019b, 2020b).

Systemwide Issues

As discussed above, the long-term viability of this method relies on salt mineralogy and its stability. This BACM does not appear to have any significant sensitivity to a warming climate, except for the possibility of increased flooding. The BACM may be susceptible to unplanned surface flooding, which would dissolve both evaporite and capillary crust, potentially altering the salt chemistry. However, if salt chemistry is not significantly altered, this

BACM could serve some benefit as a repository for floodwaters. Further testing and analysis is needed to understand the impacts of surface flooding on the chemistry and durability of the evaporite and capillary crust on this BACM.

Its most logical application is in areas approaching the brine pool where, in the long run, salts will be accumulated. In addition, at lower elevations in the lakebed, the sites could receive drainage brines from managed vegetation BACM sites.

Information Needs to Inform Decision Making

Additional research could improve the applicability of the brine BACM as a DCM that does not use freshwater. Specifically, research on long-term salt stability and dust emissions under both dry and wet conditions is needed to understand the reliability of the measure without surface flooding backup. Research is also needed to understand the susceptibility of the capillary brine crust to thermal and geochemical changes that may affect the long-term dust control efficiency. Scheidlinger (2008a) reviewed the Owens Lake brine chemistries, and although it was concluded that development of a sodium chloride–dominated crust from the brine was challenging, the work could serve as a roadmap for innovation and understanding of future potential of the brine BACM to develop more stable salt crusts. The brine BACM has significant advantages for long-term management of salinity and could provide the basis for other BACM designs that utilize the natural geochemistry of saline minerals for dust reduction.

Tillage with Shallow Flooding BACM Backup

Tillage with the shallow flooding BACM backup was approved as a modification to the shallow flooding BACM in 2014.[6] Tillage controls soil erosion by wind and fugitive dust emissions in several ways. Tillage, as practiced on the Owens Lake bed, creates oriented beds and large surface aggregates (termed oriented and random surface roughness, respectively; see Figure 4-5). Surface roughness has long been known to reduce surface erodibility and was one of the five factors in the first predictive equation for wind erosion (Woodruff and Siddoway, 1965). In general, soil particles and aggregates greater than 0.84 mm in diameter are considered non-erodible (Chepil, 1962; Fryrear, 1984; Zobeck et al., 2003) because the aggregates are too large to be entrained in all but the most intense windstorms. By increasing the surface roughness, tillage also reduces the wind speed at the surface by shear stress partitioning and the creation of turbulent eddies. This effect on the wind field is most effective when the direction of tillage and the ridges created are perpendicular to the dominant wind flow direction. For this reason, tillage patterns that deviate from linear are more effective at

[6] District Rule 433, Control of Particulate Emissions At Owens Lake, adopted March 13, 2016. See https://ww3.arb.ca.gov/drdb/gbu/curhtml/r433.pdf (accessed January 28, 2020).

FIGURE 4-5 Dust control using tillage with shallow flooding BACM backup.
SOURCE: Photo courtesy of David Allen, panel member.

reducing surface wind speed for winds of all directions. Finally, the surface ridges and clods provide shelter angle protection that prevents wind-carried sand particles from striking a flat horizontal surface and ejecting more particles (Potter et al., 1990).

The tillage with shallow flooding BACM backup requires that a roughness value of <10 (defined as the ridge spacing [RS] to ridge height [RH]) be maintained along with a ridge height of greater than 1.3 feet. In addition, measurements, including the induced particle emission test and sand flux, are required to assess the dust control performance. If the control efficiency measurements show insufficient dust control, the area is flooded and tilled again to renew the surface roughness.[7]

[7] District Rule 433, Control of Particulate Emissions At Owens Lake, adopted March 13, 2016. See https://ww3.arb.ca.gov/drdb/gbu/curhtml/r433.pdf (accessed January 28, 2020).

Performance

Tillage is a proven method for reducing surface erodibility (Fryrear, 1984; Potter et al., 1990). Studies at Owens Lake showed that when the performance criteria were maintained, tillage generally resulted in *de minimis* levels of sand flux and PM_{10},[8] which was considered equivalent to a control efficiency of 99 percent or greater sand flux (Air Sciences, Inc., 2015). Exceedances were attributed to the tilling events, construction activities, and off-site sources. The field tests at T12 in heavy clay soils were tilled to achieve a ridge spacing of 12-14 feet and ridge heights of 1.6-2 feet (total distance between furrow bottom and ridge top of 3.2-4 feet), resulting in starting roughness values between 6 and 8.75,[9] although the furrow depths and ridge heights did decrease somewhat over time. Different tilling spacing was not tested. There was no contemporaneous untreated control area during the evaluation of tillage performance, but several years of pre-tillage horizontal mass flux measurements were made at dust control area T12. In addition, the tillage test at T12 is one of the few DCMs to have performance evaluated using direct measures of PM_{10} at upwind and downwind locations. Tillage can also benefit adjacent dust control areas because the aerodynamic roughness it creates can slow near-surface wind speeds immediately in the lee of the tilled area.

Practical Considerations

Tillage with BACM backup can be installed and become fully functional quickly. Thus, it is especially suitable for emergency use. One limitation of emergency tillage is that the soil must be moist to allow for tillage and formation of large aggregates.

A single intense rain event can break down the aggregates in sandy soils to produce erodible particles. Tillage is most effective and durable in soils with sufficient clay content (greater than 50 percent clay content) to form aggregates with high mechanical strength (Cox, 1996a). It is used primarily on the tighter textured soils of the lakebed at present. In areas with clay-rich sediments, tillage is estimated to be effective for 5 years (Valenzuela, 2019b). Areas with sandy sediments may need tillage-induced roughness renewal more frequently than annually depending on rainfall or mechanical forces such as freezing and thawing of moist aggregates.

[8] "The *de minimis* criterion for the tillage BACM test based on the daily sand mass consisted of the following: If the maximum area-average daily sand mass was less than one gram, the site was considered to meet *de minimis*. . . . The value of one gram represents a 99-percent reduction in sand motion from the sand fluxes that flagged area T12-1 for dust control in 2005." (Air Sciences, Inc., 2015). Several criteria were used to determine the *de minimis* threshold for PM_{10}. For example, step 1 of the criteria states: "The de minimis threshold is an observed 24-hour PM_{10} concentration difference between the upwind and downwind monitor ($\Delta\chi$) at the downwind TEOM of <100 μg m^{-3} (μg/m^3). The logic behind this screen is that if the Tillage test area does not add more than 150 μg m^{-3} at the downwind TEOM, then the area should not produce an exceedance of the federal 24-hour PM_{10} standard (150 μg m^3) at the shoreline because any dust plume that leaves the area will be reduced by atmospheric dispersion before it reaches the shoreline. Lowering the screen from 150 to 100 μg m^{-3} adds an extra level of conservatism. The value of 100 μg m^{-3} represents a 99-percent reduction in the modeled 24-hour PM_{10} concentration that flagged area T12-1 for dust control in 2005 (based on District calculations)."

[9] District Rule 433, Control of Particulate Emissions At Owens Lake, adopted March 13, 2016, Appendix C. See https://ww3.arb.ca.gov/drdb/gbu/curhtml/r433.pdf (accessed January 28, 2020).

Water Use

Tillage requires no water for routine maintenance (Valenzuela, 2019b). However, water application is typically necessary before tillage to produce large, indurate aggregates, and this water also minimizes dust during tillage. Water may also be needed for shallow flooding to control emissions if the tillage fails. If tillage renewal immediately follows the rainy season, it is possible that no water additions would be required.

Environmental Implications

Tillage has little habitat value other than a minimal potential for creating microhabitats for small vertebrates and invertebrates, and it is more likely to decrease the small baseline habitat potential of the barren playa. Because of the possibility of bacterial oxidation of any accumulated organic material in the tilled sediments, tillage may result in increased carbon dioxide (CO_2) emissions from the lakebed. Tillage is destructive by nature and buries the surface. Thus, tillage would damage or destroy cultural resources. Additionally, tillage provides little aesthetic value.

Energy Use

Tillage of heavy clay soils to the depth mandated for this BACM requires the use of large tractors with high horsepower and fuel consumption.[10] Following tillage, continual energy use is limited to that necessary to monitor performance, which is currently provided by photovoltaic panels.

Cost

Tillage is one of the most cost-effective DCMs available. The primary capital costs to establish a tillage plot are fuel, manpower, and amortization of equipment. According to LADWP, tillage costs $500,000/square mile to establish, and annual operating costs are $1.48 million/square mile (Valenzuela, 2019b). Operational costs include monitoring of control efficiency, roughness, crusting, and surface integrity as well as any flooding and repeat tillage needed for maintenance.

Systemwide Issues

Intense rain events are predicted to become more frequent with climate change. Thus, the durability of the tillage BACM could decline over time.

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[10] With tillage estimates of 130 hours/square mile (assuming a tillage rate of 4 km/hour (2.5 mph) and tillage spacing of 5 m (16.4 feet) and 17.6 gallons/hour using a 400-horsepower tractor (Grisso et al., 2014), fuel use is estimated at 2,300 gallons/square mile.

Managed Vegetation

The managed vegetation BACM establishes locally adapted native vegetation into dust-emissive areas. Its initial implementation was restricted to saltgrass (*Distichlis spicata*), but in 2016 the species list for the managed vegetation BACM was expanded to include 47 additional species with a range of salinity tolerance, drought tolerance, flooding tolerance, rooting depth, and morphology. This increased palette of species allows for more diverse and resilient plant communities that can control dust through multiple pathways and maintain vegetation cover under variable conditions. At present, the vast majority of managed vegetation areas have been planted with saltgrass, and all data and evaluations below focus on stands of this species.

Vegetation can control dust by three key mechanisms: (1) covering and protecting the soil surface from wind, (2) decreasing wind energy at the soil surface, and (3) trapping dust particles that blow from or into the site. The relative importance of these mechanisms varies based on vegetation density, size, and morphology. In saltgrass stands, dust control is largely mediated through protecting the soil surface from the wind (reviewed in Lancaster and Baas, 1998) (see Figure 4-6).

FIGURE 4-6 Managed vegetation BACM on Owens Lake. Vegetation protects the soil surface from the wind, and small patches of bare ground are not emissive.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

Performance

Studies of the initial implementations of managed vegetation at Owens Lake evaluated the impact of percent cover of saltgrass on sand flux, as well as the related effects on PM_{10} emissions along the regulatory shoreline. An early small-scale study on a sandy area of Owens Lake found that 17.5 percent cover of saltgrass decreases sand flux by 95 percent (Lancaster and Baas, 1998).

The current vegetation cover requirements for this BACM are derived from a study of the largest area of managed vegetation on Owens Lake—2,100 acres in the southern end of the lake. Vegetation at this site was allowed to establish for 2 years (2002-2004), and then was monitored for 2 years. Sand flux decreased by an average of 99 percent (range of 97-100 percent) when vegetation cover was at least 20 percent. Plots with vegetated cover between 1 and 20 percent (with more than half of the plots being greater than 10 percent cover) resulted in an average of 97 percent decrease in sand flux (with a range of 82-100 percent) (Schaaf and Schreuder, 2006). Based on this study, 20 percent vegetation cover was established as the required minimum at any point in the year. Because vegetation sampling occurs in the fall, and vegetation cover can decrease by 10 percentage points over the winter dormancy period, leading to lowest vegetation cover in the springtime, the minimum fall vegetation cover was set at 30 percent.

Methods of assessing vegetation cover have varied over time (e.g., from point sampling to digital point sampling and satellite remote sensing methods) and by agency. Substantial effort resulted in standardized monitoring methods across the agencies involved in Owens Lake, with calibrations across the multiple ground methods and satellite measures (NewFields et al., 2007). As vegetation sampling methods shifted, the methods were calibrated, and the 30 percent vegetation cover under old vegetation sampling techniques was determined to be equivalent to 39 percent cover with new vegetation sampling techniques (NewFields et al., 2008). It is unclear how 39 percent was adjusted to 37 percent cover, but given the high dust control of much lower vegetation cover, it is likely that this current threshold is still conservative (Schaaf and Schreuder, 2006). Percent cover requirements could be refined with analyses of monitoring data using narrower vegetation cover categories.

Based on these initial data, surface cover of vegetation has become the primary performance measure for the managed vegetation BACM. Vegetation cover is assessed every fall (between September 21 and December 21) using satellite imagery that quantifies percent cover of vegetation. These images are then ground-truthed using digital point frames (GBUAPCB, 2016a). The BACM requires an average 37 percent vegetation cover, but it acknowledges that vegetation cover can be patchy and that small areas of lower vegetation cover will not be emissive. Standards for assessing suitable levels of patchiness at various grid scales are provided in the SIP (GBUAPCB, 2016a). As the patch size increases (e.g., from 0.1 to 100 acres), there are requirements for a higher percentage of the area to achieve each threshold of vegetation cover; for example, at a grid scale of 100 acres, there is less tolerance for low-vegetation cover patches than at 0.1 acre.

Arid systems experience substantial edge effects, with the windward edge being more emissive as it takes the brunt of the wind force (Buckley, 1987). Thus, the overall effectiveness of dust control also depends on the size of managed vegetation units and whether they are adjacent to other DCMs that decrease wind force (e.g., roughness elements, tillage).

Practical Considerations

Managed vegetation dust control plots require at least 2 to 3 years to establish (Schaaf and Schreuder, 2006), so this approach is not suitable as an emergency response in an emissive area. In fact, weather variability or setbacks in construction scheduling can challenge full establishment of this BACM within the 3-year permitting and compliance window required by the agencies for BACM transitions. The establishment phase typically requires five key steps: (1) installing flood control infrastructure to prevent flood damage to the area, (2) installing tile drains and pumps if needed to lower shallow saline groundwater levels, (3) leaching salts from the soil, (4) planting vegetation, and (5) maintaining and enhancing vegetation. Delivering water to plants can be challenging. Drip irrigation, while water efficient, has high rates of emitter failure, particularly with saline water. Where flood irrigation is used in sandy soils, furrows are critical to water delivery to the plants. A long-term challenge is preventing salt accumulation, which can be caused by excessive irrigation (high cumulative salt input over time) and poor drainage, or low or sporadic irrigation rates (which over time can add salts but fail to flush salts out of the rooting zone) (Scheidlinger, 2008b).

The most vulnerable time period for this BACM is at the establishment phase. Under windy conditions, sowed seeds can blow away (Scheidlinger, 2008b). Wet years can be particularly challenging for vegetation establishment, because saline groundwater can rise into the rooting zone, and seedlings are especially sensitive to salinity (Burgess and Schaaf, 2019). Seedlings are also more vulnerable than mature plants to damage and mortality through sand blasting (Scheidlinger, 2008b). Hybrid dust control approaches may be useful during plant establishment, such as artificial roughness or precision surface wetting, discussed later in this chapter.

Once established, vegetation cover and its dust control are durable and reliable over the long term, as long as appropriate salinity conditions are maintained (Scheidlinger, 2008b). In 2002, 2,240 acres of managed vegetation were planted and achieved an average of 42 percent vegetation cover. Only 400 acres had poor establishment, and once these areas received modifications in drainage and replanting, all but 11 acres were in compliance (GBUAPCD, 2016a). The sites with long-term vegetation cover declines are usually not suitable for managed vegetation, or soil salinity was not sufficiently remediated prior to planting (Scheidlinger, 2008b).

Vegetation cover can decrease in the short term in response to floods (saltgrass has low flood tolerance), rising groundwater in wet years, surface ponding, and unexplained declines, but most areas recover within a couple years. With managed vegetation BACMs, vegetation cover generally is only weakly affected by lower precipitation years and can survive at least one season without irrigation, as long as there is no saltwater intrusion (Scheidlinger, 2008b). Temporary decreases in vegetation cover may not impact PM_{10} emissions because dead vegetation can persist for at least 3 years and provide similar dust control as live vegetation, allowing for a 3-year temporal buffer of dust control while vegetation recovers (Scheidlinger, 1997). In addition, the relatively conservative threshold of required percent cover ensures that dust emissions are minimal, although managed vegetation dust control areas can be non-compliant at times (LADWP, 2018).

Achieving the full potential of this BACM over the long term would be aided by a more flexible regulatory timeline at establishment, because strict time frames are not realistic for establishment of a biological system. For example, leaching salts from sandy soils can be relatively easy, but may require many rounds of flooding and leaching in clay soils. These initial delays can lead to managers missing the two short planting windows that are available each year to establish vegetation (Scheidlinger, 2008b). Similarly, vegetation establishment and spread can vary based on annual weather conditions or level of remediation of soil salinity. Even when initial establishment is low, saltgrass rhizomes spread (Trimble, 1999) and would likely achieve the targeted percent cover given more time. However, under the current regulatory time frame of 3 years to meet performance criteria (Board Order 160413-01), there is no flexibility to allow this to occur. For example, the panel visited a managed vegetation site that will be converted to shallow flooding because vegetation cover was slightly below the required threshold, even though the site contained a healthy-looking saltgrass stand.

The extensive list of conditions that must be managed for vegetation establishment and maintenance highlights the diverse conditions necessary for plant cover. Thus, it is not surprising that site-specific conditions (e.g., soil type, salinity, groundwater depth, quality of irrigation source water) will strongly impact the management practices, costs, and potential of sites for vegetation establishment across the lake (LADWP, 2010; Scheidlinger, 2008b). Box 4-1 describes some of the location-specific factors that impact the performance and water use of the managed vegetation BACM. Of the projects implemented on Owens Lake, most managed vegetation BACMs were located on mudflat and saltcrust areas, which are more difficult to leach and maintain salinity. This likely skews existing water and cost data to more expensive, more long-term maintenance scenarios, compared to managed vegetation efforts focused on sandy areas of the lake that have been leached with freshwater from shallow flooding, or areas closer to the regulatory shoreline, which tend to be sandy, less saline, and with deeper groundwater. With the expanded species palette, it is likely that better matching of vegetation to site conditions will improve effectiveness of this BACM and will result in fewer costs and less maintenance. The more diverse vegetation choices recently approved also provide options for dust control from off-lake emissive areas.

Box 4-1
Soil Type and Location Influences Practical Considerations for the Managed Vegetation BACM

Although vegetation can establish well on both sandy and clay soils, soil texture (see Figure 4-7) is one of the most important variables that affect the types and level of maintenance required for managed vegetation.

As demonstrated across a suite of trials at Owens Lake, sandy sites tend to be easier to reclaim and maintain than clay-rich sites (Scheidlinger, 2008b). This finding is further supported by frequent self-recruitment of saltgrass on sandy areas exposed to shallow flooding and other irrigation (GBUAPCD, 2016a), and by the fact that saltgrass increases density and expands outward more quickly in sand than in clay (Scheidlinger, 2008b). Sandy soils are more easily leached of salts and require less water for leaching, because of better infiltration and drainage. Leaching of salts can occur with as little as 0.1 ft flooding depth over a 2-week period (as demonstrated in the Vegetation on Sand Trial of 2000; Scheidlinger, 2008b). Leaching of sandy soils is best achieved with drip or furrow irrigation, because flood irrigation results in rapid infiltration and patchiness in the areas that are leached. In sandy areas with shallow groundwater, tile drains can be placed further apart (800 ft distance compared to 160 ft distance in heavy clay soils) to maintain deeper groundwater levels, also reducing costs (Scheidlinger, 2008b). Sandy soils do have lower water-holding capacity, so these areas require early season irrigation to support plant growth, which is not required in clay soils (Scheidlinger, 2008b).

The perception that managed vegetation would be more successful in clay soils emerged from early managed vegetation trials, when leaching of salts from soils was predominantly achieved by flood irrigation. Under these conditions, uniform leaching of salts was easier from clays than sand, especially when the surface soil was disked or tilled to destroy surface cracks that would prevent uniform surface flooding (Scheidlinger, 2008b). Clay soils require more water to leach out salts (e.g., 4.0-7.9 ft of water to reclaim the top 2 ft of soil), and they have a higher probability of not being reclaimed, as demonstrated by some areas in the 1997 Large Panel trial, where electrical conductivity was high even after six cycles of leaching (Scheidlinger, 2008b). Ensuring that saline groundwater remains below the rooting zone in clay soils requires a higher density of tile drains than in sand, and often extensive pumping of this saline water off site. Managing soil salinity over the long term is a balancing act in clay soils. Soil that is too saline can stunt or kill vegetation, while long-term removal of salts from clay-rich soil can lead to collapse of the clay structure, destroying the soil potential for infiltration and leaching. Although there is little evidence of collapse occurring at Owens Lake, it can be prevented by using irrigation water that mixes saline and freshwater to achieve an electrical conductivity of 9 decisiemens per meter (Scheidlinger, 2008b).

With the recent increase in the types of plant species and communities used for managed vegetation, soil type (along with salinity and groundwater levels) should be an important consideration in which species should be planted in which locations.

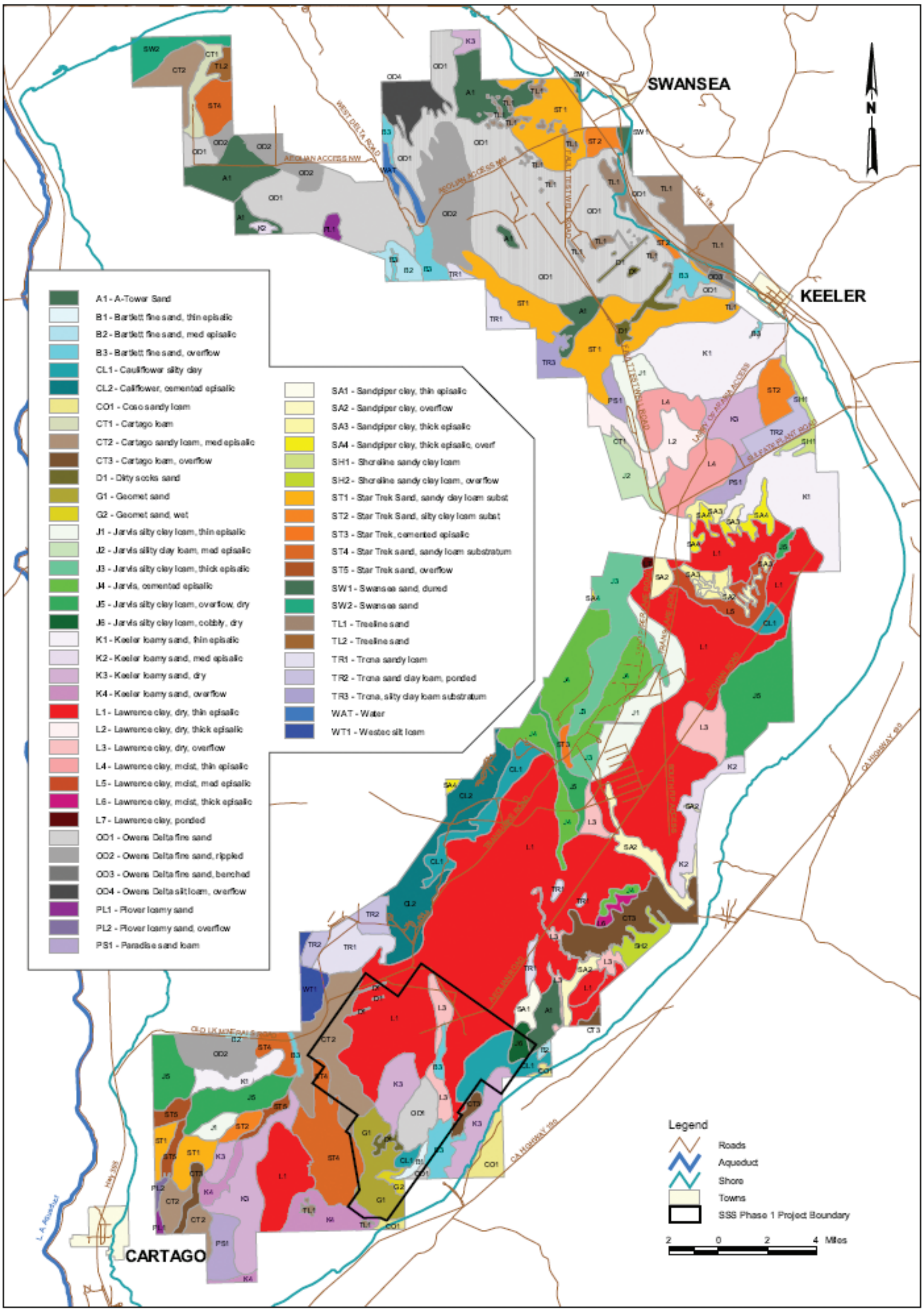

FIGURE 4-7 Soil texture map.
SOURCE: LADWP and GBUAPCD, 2002.

Water Use

Water use to establish managed vegetation can vary greatly, depending on soil texture and salinity. The amount of water to flush salts from the rooting zone of the soil can vary from 0.1 ft to more than 8 ft of water (Scheidlinger, 2008b). Establishing vegetation can require 1.2-4.0 ft/year, and current irrigation rates on established vegetation range from 1.1 acre-ft/year for drip irrigation to 1.5-2.65 acre-ft/year with sprinklers (Valenzuela, 2019b). It is not clear how much of the water use difference between sprinklers and drip irrigation is due to evaporation and how much is related to the soil types on which these irrigation systems are applied. Long-term irrigation needs are likely far lower, and saltgrass can withstand at least 1 year of no irrigation (Scheidlinger, 2008b). With the expanded palette of species available under the managed vegetation BACM, the required water use will range widely, with the potential for some of the dryland species to require minimal water beyond the establishment phase.

The salinity of water applied to managed vegetation is critical, with the value depending on vegetation type and soil texture. Care must be taken to minimize long-term salt accumulation due to irrigation (Scheidlinger, 2008b).

Environmental Implications

Dry alkali meadows, such as the saltgrass planted as part of the managed vegetation BACM, are a regional hotspot for ecosystem productivity and community diversity (LADWP, 2010; Pavlik, 2008; see Figure 4-8). In fact, managed vegetation areas on Owens Lake are used to fulfill mitigation requirements due to habitat destruction in other parts of the lake (GBUAPCD, 2016a). Saltgrass meadows can provide habitat for diverse invertebrates (e.g., ants, spiders, grasshoppers, and crickets), birds (e.g., Savannah Sparrow, Horned Lark, and American Kestrel), and small mammals (e.g., kangaroo rat, mice, gophers, and rabbits). Reptiles are expected but not confirmed. When adjacent to shallow flooding areas, managed vegetation can also provide important resting habitat for waterbird species such as the Long-billed Curlew and Wilson's Phalarope (LADWP, 2010). The expanded species list for the managed vegetation BACM allows for creation of additional habitats, including alkali marsh, playa scrub, and freshwater marsh and riparian systems.

Managed vegetation meets the California Public Trust, providing aesthetics, valuable habitat, and recreational activities. Areas that require high infrastructure for vegetation establishment (e.g., tile drains, irrigation infrastructure) are not compatible with cultural resources.

Energy Use

As with water, long-term maintenance, and thus energy use will largely be determined by site conditions. Because most of the dust producing areas have saline groundwater in or near the rooting zones, these will require pumping from the drainage system during most of the year, resulting in ongoing energy use. Areas of coarse textured soils, such as often found near

FIGURE 4-8 In addition to saltgrass, other alkali meadow species recruit into managed vegetation parcels. SOURCE: Photo courtesy of Valerie Eviner, panel member.

the historic shoreline and in the northern portion of the lakebed may, over time, become sufficiently leached and naturally drained that they will not need a managed drainage system.

Cost

To implement the sprinkler approach to managed vegetation in Phases 7a, 9, and 10 of Owens Lake dust control, establishment of the BACM required $36 million/square mile in capital costs, while the drip irrigation–based managed vegetation farm initially cost $20 million/square mile. These initial costs included soil reclamation, mass grading, subsurface draining materials, planting materials, and extra fees due to a compressed construction schedule to meet the narrow planting window. As described in the previous section on practical considerations, the logistics of setup and maintenance of managed vegetation can be extremely variable depending on groundwater, salinity, soil texture, and weather conditions at the time of planting. For the most part, managed vegetation has been applied to areas that would incur higher costs due to relatively clay-rich soils with shallow and saline groundwater. This decision was partly based on setup costs, including more irrigation, but more so on the need to perpetually maintain groundwater levels through tile drains and pumping. Annual operating costs are currently $2.35 million/square mile for the sprinkler approach and $1.64 million/square mile for the drip irrigation approach. Routine maintenance includes repairing irrigation leaks, fertilizing approximately once a year, and cleaning irrigation filters. Costs could be decreased by focusing on areas where long-term maintenance would be minimal, such as in lower-salinity sandy soils near the lakeshore, and in sandy soils in the playa already leached of salts, where vegetation is naturally establishing (LADWP, 2010).

Over the long term, irrigation and drainage infrastructure and pumps will need to be periodically replaced. LADWP estimates that this infrastructure will last 20 years, and will require complete reestablishment costs at that time.

Systemwide Considerations

Long-term management of groundwater levels and salinity are the most critical factors for durability and reliability of the managed vegetation BACM. These factors are highly dependent on siting considerations (e.g., soil type, depth to groundwater). Adjacent dust control areas can also influence the durability of managed vegetation parcels. For example, dieback of saltgrass occurred due to a rise in saline groundwater during construction of an adjacent dust control area (Scheidlinger, 2008b). Because long-term vegetation vigor depends on keeping saline groundwater below the rooting zone, managed vegetation in large contiguous areas (e.g., those in the southeast part of the lake) are beneficial (Scheidlinger, 2008b). Placing managed vegetation adjacent to freshwater BACMs can allow for natural vegetation spread into those areas, increasing not only dust control over the long term, but also groundwater levels. Another important consideration in adjacency is that the tile drains avoid impacting the surface water or groundwater of existing wetlands (GBUAPCD, 2016a).

System-level considerations will become critical under climate change. Increased temperatures, particularly during the summer, will increase evapotranspiration and can exacerbate plant water limitations. However, changes in precipitation patterns will likely be the greatest challenge to managing vegetation. Year to year, precipitation will be highly variable, and high precipitation years could cause uncontrolled flooding and increases in saline groundwater levels. Saltgrass is one of the most salinity-tolerant species approved for managed vegetation, although it is highly susceptible to saline groundwater intrusion into the rooting zone (Scheidlinger, 2008b). Other species will likely be even more susceptible to saline groundwater. An increase in the diversity of species used in managed vegetation can increase the stability of vegetation cover under fluctuating conditions (Hector et al., 2010; Isbell et al., 2015), especially in the parts of the lake with deeper groundwater and lower salinity, where salinity mortality associated with rising groundwater is unlikely.

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

Information Needs to Inform Decision Making

The largest improvement in the managed vegetation BACM also reflects the largest information gap. Although the number of approved species has increased from 1 to 48 and the number of ecosystem types has increased from 1 to 4, there is little data on any species other than saltgrass at Owens Lake in terms of management needs for establishment, and on resilience and reliability due to short- and long-term environmental changes. Similarly, there is a need to understand the performance and functioning of different vegetation species, including habitat provisioning, dust control, and effects of salinity. Also needed is evaluation of how diverse plantings differ from monocultures in terms of performance and ecosystem effects. Diverse plantings are particularly important because they can often enhance the delivery of multiple ecosystem services, minimizing the tradeoffs associated with any single species (Lefcheck et al., 2015; Maestre et al., 2012; van der Plas et al., 2016; Zavaleta et al., 2010).

Another unanswered question is the extent to which these vegetation communities can maintain themselves over the long term, minimizing the need for perpetual management and thus decreasing costs and water use. For example, woody species have been used in other semi-arid systems to lower the groundwater table and to prevent saline groundwater from intruding into rooting zones (Bell et al., 1990), which would be an important tool if possible with the species and conditions at Owens Lake.

A key challenge lies in how to design plant communities to withstand the projected increases in extreme weather conditions year to year, with expected fluctuations between multiyear droughts and intense flooding associated with more rapid snow melt, more intense storms, and high rainfall El Niño years. Extremes in precipitation will be compounded by increased temperatures leading to higher evapotranspiration. Another challenge lies in how to manage salinity over the long term in a terminal alkali basin where salts naturally accumulate. This answer is critical, not only because of vegetation requirements but also because clay soil structures can collapse if salinity is greatly reduced. Other pressing questions for Owens Lake include where are the most appropriate areas for specific plant types and communities used in managed vegetation BACMs, how large must these vegetated areas be to minimize required maintenance, and how are they affected by adjacent dust control measures?

The ways in which natural spatial and temporal variability in vegetation impacts dust control is another important consideration, because the strict regulations of time frames and threshold percent vegetation cover values are not always realistic in an ecological system, where variability is the norm but ecosystem services can be maintained despite this variability. Understanding whether lower percent cover (especially of more diverse vegetation communities) can achieve dust control is important, because the long-term durability, effectiveness, and self-maintenance of managed vegetation may be worth the tradeoffs of short-term decreases in vegetation cover due to environmental variability or delays in vegetation establishment.

Current models poorly predict the effects of vegetation cover on dust control, because they do not adequately account for vegetation clumpiness or changing wind direction (Okin, 2008; Okin et al., 2006) and monitoring by satellite remote sensing (as currently done at Owens Lake) does not allow for quantification of the patchiness of vegetation on the ground. Studies could examine the value of higher resolution data using airborne imagery or unmanned aerial systems (i.e., drones; Cunliffe et al. 2016) and their capabilities with visual and hyperspectral cameras.

Gravel

Gravel cover is a zero-water-use DCM that involves distributing a layer of gravel on an emissive lakebed to protect it from wind (see Figure 4-9). Gravel protects the bare ground underneath it against wind erosion by substantially reducing the capillary rise of saline groundwater and salt and crust formation.

Some areas are covered by 4 inches of gravel (GBAPCD, 2003), while others are covered by 2 inches, underlain with a permanent permeable geotextile fabric to prevent settling of the gravel (GBAPCD, 2013b). The gravel, which is mined and transported to the site, is required to be of similar color to that of the lakebed soils and be at least 0.5 inches in diameter. The geotextile fabric is a 2.3-mm thick (90 mils) artificial fabric that is permeable to draining

FIGURE 4-9 Dust control using the gravel BACM.
SOURCE: Photo courtesy of Stephanie Johnson, National Academies.

and resistant against acids and alkali elements of the soils. To protect the gravel-covered area from flooding, channels and drains are incorporated in the area surrounding the control area (GBUAPCD, 2008, 2013b).

Performance

The District has estimated that PM_{10} emissions from an area covered with gravel with the specifications listed above will be reduced by 100 percent given the expected highest wind speeds at the lakebed. This estimate is based on a study that found that a gravel layer, with stone sizes of 0.25 inches in diameter and larger, has an entrainment wind velocity threshold of more than 90 mph (measured at 10 m [32.8 feet]) (GBUAPCD, 2008; Ono and Keisler, 1996). The District investigated the effectiveness of a gravel blanket to prevent salt accumulation at the surface (efflorescence) at two sites in June 1986 and concluded that the salt efflorescence was prevented in plots covered by 4 inches of 0.5- to 1.5-inch diameter gravel (Cox, 1996b).

Practical Considerations

The effectiveness of the gravel BACM is immediate when an emissive area is fully covered as described above. However, if applied in areas adjacent/downwind of emissive surfaces, its effectiveness is compromised because sand and silt from upwind emissive regions may fill the gaps or cover the gravel, allowing greater capillary rise of saline water and salt efflorescence at the surface, making them prone to secondary emissions. Given the time it takes to prepare a site for gravel distribution, gravel is not suitable as an emergency control.

Areas covered by gravel are monitored visually each year for signs of dust and sand accumulation, washouts, or inundation (GBUAPCD, 2013c). When fine sands and silts fill the gaps in the gravel, capillary rise of saline groundwater will increase, lowering gravel's effectiveness for dust control (Cox, 1996b). When deterioration in gravel coverage is observed in areas larger than 1 acre, the gravel will be raked to allow the fines to settle toward the bottom. If raking cannot restore target control efficiencies, additional gravel can be brought to the site. Gravel as a DCM is expected to last for decades; it is estimated that the gravel used during phase 7a (total area of 1.5 square miles) will need to be replenished in 50 years after installation (GBUAPCD, 2013d) although LADWP staff estimate a 20-year lifespan for the gravel BACM (Valenzuela, 2019b). Overall, little maintenance is expected for gravel cover unless it is adjacent to uncontrolled emissions where dust deposition on gravel would trigger the need for raking.

Water Use

No water use is required at any point in the installation or maintenance of the gravel BACM.

Environmental Implications

Overall, gravel provides relatively low-quality habitat relative to other DCMs. Distribution of gravel prevents vegetation growth; however, if placed adjacent to shallow-flooding areas, it can provide some nesting habitat for shorebirds. Continuation of gravel mining from nearby resources may negatively impact the sensitive areas surrounding the mine while also leaving a negative visual sight at the mines. Mining, transport, and distribution of the gravel will also lead to emissions of some other atmospheric pollutants (e.g., soot, nitrogen oxides, CO_2, and hydrocarbons).

Gravel also has low aesthetic value. Because installation and maintenance requires heavy machinery, the BACM is not suitable for environmentally sensitive areas.

Energy Use

Energy associated with the gravel BACM is used during gravel mining, gravel transport to and within Owens Lake, site preparation, and installation. For a 4-inch layer of gravel, an average of 510,000 tons of gravel are distributed per square mile (LADWP, 2013). With an average energy consumption rate of approximately 17 megawatt hours/ton in mining of industrial minerals (e.g., gravel) (BCS Incorporated, 2007), mining of gravel alone is estimated to use 8.7 million megawatt hours/square mile. In addition, assuming trucks can carry approximately 25 tons of gravel per trip (LADWP, 2013), 20,000 trips/square mile are needed to move the gravel from the mining site to the gravel stockpile on the lake and from the stockpile to the final dust control location. Total energy associated with transporting gravel depends on the distances traveled in each trip and the truck's engine efficiency. Equipment used during land leveling, distribution of the geotextile fabric, and distribution of the gravel also contribute to the total energy use associated with the gravel BACM. Energy use is most intense during the installation and is expected to be significantly lower during the life of the gravel BACM because of its low maintenance.

Cost

LADWP engineers estimate the capital costs associated with the gravel BACM to be $37 million/square mile. Annual operating costs are $230,000/square mile.

Systemwide Issues

The gravel BACM is resilient against climate change except in the events of extreme precipitation/flooding, which causes either transport of sediments over the gravel or displacement of the gravel itself.

OTHER NON-BACM DUST CONTROL MEASURES

The panel reviewed nine other DCMs that show potential for use in dust control on the Owens Lake bed. Some of the measures also show potential for control of off-lake sources.

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

Precision Surface Wetting

Precision surface wetting as demonstrated in the Shallow Flooding Wetness Curve Refinement Field Test (SFWCRFT; LADWP, 2019b) represents a modification to the existing shallow flooding BACM. Precision surface wetting utilizes reciprocating sprinklers or perforated whip lines to wet circular areas of the lakebed to target a specific wetted percentage. Testing has been conducted in the SFWCRFT to examine approaches to using precision surface wetting to reduce water use while controlling dust emissions.

Precision surface wetting controls wind-induced erosion of soils and the resultant PM_{10} emissions by several mechanisms. First, individual grains on moist surfaces are linked by water molecules to form cohesive surfaces requiring much greater energy to entrain (Ravi et al., 2006). In addition, the presence of free or near-free water on the surface and in the air from sprinkler droplets tend to increase the humidity in the laminar boundary layer over and downwind of the wetted circle. Humidity above a certain threshold has been shown to inhibit dust entrainment (Ravi and D'Odorico, 2005; Ravi et al., 2004). Finally, for soils in-between the wetted circles, any particles entrained by the wind would eventually impact a wetted circle and lodge in the moist surface or collide with a sprinkler droplet and become wet deposition on the surface (Stulov et al., 1978).

Performance

The SFWCRFT examined the dust control at different wetted percentages up to 75 percent wetted area at four locations on the Owens Lake bed and LADWP has proposed additional testing (LADWP, 2019b). The sprinklers and whip lines operated during the dust control season from October 15 to May 15, although some challenges were observed in sustaining the target wetted areas throughout the dust season (Air Sciences, Inc., 2016). Performance was assessed with the proxy measurement of horizontal mass flux using Cox Sand Catchers and Sensits along with remote cameras that record dust plume emissions. The test included an unwetted control at each location, providing contemporaneous measurements to calculate the control efficiency for each wind event or measurement interval.

Preliminary data show promise for use of this approach to control PM_{10} emissions while potentially saving water (Air Sciences, Inc., 2016). At the sandy sediment site, the reported average of monthly control efficiencies for the 2015-2016 dust season were 96.4 percent, 97.7 percent, 99.4 percent, and 99.0 percent for the 45 percent, 55 percent, 65 percent, and 75 percent wetted cover treatments, respectively. Given the extent of volunteer vegetation at these sites, with mature vegetation, it may be possible to achieve BACM levels of dust control with lower wetted cover.

Practical Considerations

This DCM requires substantial water distribution infrastructure and therefore is not suitable for emergency use. Sprinklers or whip lines will be more effective than laterals, because water from low-pressure lateral piping tends to follow microtopographic depressions and thus not wet a uniform and predictable area. Sprinklers, valves, and pumps are built with moving parts that wear and may corrode in the saline environment of Owens Lake. They will need to be replaced on a periodic basis and represent a perpetual material and labor expense. LADWP reported the expected lifespan of sprinklers to be 20 years (Valenzuela, 2019b). If properly maintained and operated, precision surface wetting should be a very reliable DCM.

Water Use

Because of the increased application efficiency inherent with sprinklers and other orifice-controlled application methods over simple standpipe flooding (Letey et al., 2007), this DCM is expected to use applied water more efficiently than shallow flooding. The water use needed for precision surface wetting remains uncertain, because the pilot testing failed to consistently maintain the target wetted areas over time. At the sandy site during the 2015-2016 dust season, two treatments reported 99 percent control efficiencies, as mentioned above. An average water use of 2.0 ft/year was reported from the 65 percent wetted cover treatment but met the target wetness for only 4 months. Likewise, an average water use of 2.3 ft/year was reported from the 75 percent wetted cover treatment but met the target wetness for only 2 months. These amounts represent water savings compared to 3 ft/year for shallow flooding with laterals and 2.68 ft/year for shallow flooding with sprinklers. Although these data are limited, they suggest water savings may be feasible.

Environmental Implications

Precision surface wetting using sprinklers does not offer the shallow pools necessary for waterfowl and shorebird habitat. Nevertheless, at the SFWCRFT site located at a relatively high elevation on the lakebed, the sprinklers promoted vegetation that could provide valuable habitat and shelter for terrestrial birds and other vertebrates. The volunteer vegetation sustained in the wetted cover areas is possibly a surrogate for the alkali meadow habitat that is in decline locally. The capacity for precision surface wetting to support vegetation at other sites would depend on the salinity of the soil and the depth to shallow groundwater. At sites with high salinity and shallow saline groundwater, minimal vegetation could be supported, and thus at these sites, precision surface wetting would provide minimal to no habitat.

Precision surface wetting requires a large amount of distributed irrigation infrastructure with traffic to install and maintain, which would impact environmentally sensitive areas. Even though the lateral piping and sprinklers are unsightly, the colonization of the wetted cover by grasses, forbs, and shrubs would contribute to the aesthetic value, especially from a distance.

Energy Use

Installation of a precision surface wetting system involves energy use associated with transporting the pipe, sprinklers, and pumps. Energy use is required during operation to supply the water pressures necessary for sprinkler operation.

Cost

Cost estimates were not available for precision surface wetting, but they can be approximated based on the costs of shallow flooding with sprinklers. According to LADWP, the cost of shallow flooding with sprinklers, which represents similar infrastructure requirements, is $32 million/square mile. The infrastructure costs for precision surface wetting could be expected to decrease by 13 percent for each 10 percent reduction below 75 percent wetted surface coverage. Operating costs, estimated at $340,000/year based on the costs of shallow flooding with sprinklers, would consist of monitoring and maintaining the water distribution infrastructure (Valenzuela, 2019b). Although the installation costs are comparable to that for shallow flooding with sprinklers, the reduced water use would be expected to result in substantial operational cost savings.

Systemwide Issues

Climate change experts are predicting more frequent and longer duration droughts, which could impact this DCM (although less so than shallow flooding). Extreme events such as floods could damage pumps and valves.

The use of sprinklers at higher elevations in the lakebed would best support the growth of native vegetation without the additional cost and infrastructure of underdrains. Ultimately, the establishment of vegetation could reduce the need for wetted coverage, further reducing water demand. The colonization of the wetted areas would result in reduced near-surface wind speeds for a short distance downwind, potentially benefiting adjacent BACMs.

Information Needs to Inform Decision Making

More work is needed to document the percent wetted area necessary to obtain the required control efficiency. Tests of this DCM have suffered from a lack of statistical replications and the random capping of sprinklers to achieve the desired wetted area percentage. The lack of true replication impacts the scientific integrity of the test. Performance testing should be replicated in at least three locations with all wetted cover percentages including zero percent represented in each replicate. The random capping of sprinklers is probably limiting the potential control effectiveness because longer areas of fetch between wetted circles tend to favor the saltation cascades and resulting entrainment of dry sediments. The use of orifices and pressure to control the diameter of the wetted circles or simply different sprinkler spacings would improve the design and would limit the fetch distances of unwetted and unprotected surfaces. In addition, alternating the placement of the sprinklers on adjacent supply lines would more fully limit the possibility of long distances of unwetted surface aligning with the wind direction.

Understanding of the surface soil moisture level will be critical to reducing water use while preventing PM_{10} emissions. LADWP has an ongoing pilot study on soil moisture sensors that rely on the electromagnetic properties of the soil to determine water content and its variation with depth. However, these measurements are unlikely to provide useful data on the soil water content at the surface, the most vulnerable portion of the profile. Such sensors have been shown to be inaccurate in saline soils (Schwartz et al., 2018), and the estimates are integrated over a measurement volume of approximately 1 liter. McKenna Neuman et al. (2018) noted that even though the vertically integrated gravimetric water content (GWC) varied by less than 5 percent during a 2- to 3-day drying period, the surface water content in the upper 1 mm of soil decreased from about 25 percent to as low as 2-3 percent. LADWP should instead examine infrared thermometry to estimate surface and near-surface wetness. Infrared thermometry has long been used to estimate the evaporation rate of the soil surface, a function of surface and near-surface GWC (Evett et al., 1994; Qiu et al., 1999; Qiu and Ben-Asher, 2010). Other low-cost techniques to measure soil surface temperature and soil moisture content at high spatial resolution are also becoming more available, including fiber-optic based approaches (Sayde et al., 2010; Steele-Dunne et al., 2010). These measurements can be automated, are inexpensive, and would provide uninterrupted data on ground conditions between remote sensing images.

Among the advantages of precision surface wetting is the potential for dynamic operations based on climatic conditions. During periods with predicted wind velocities less than threshold, it would not be necessary to keep the wetted circles near saturation. Instead, sprinklers could be operated periodically to keep colonizing vegetation healthy, with additional sprinkler operation only a few hours before and during predicted high wind speed events. Trials of this dynamic precision surface wetting could be undertaken on smaller plots as part of the replicated field trials to test the effectiveness and water savings of this approach. Use of dynamic operations would necessitate alternate, real-time performance criteria, such as cameras and low-cost PM_{10} sensors along the DCM boundary.

Additional research could examine the use of precision surface wetting to build surface evaporite crusts that might eventually control dust emissions with less or no water use. According to McKenna Neuman et al. (2018), wetting the surface and allowing it to dry resulted in the formation of evaporites, aggregates too large to be entrained, and/or a surface crust that, if not disturbed, reduced dust emissions by at least three orders of magnitude compared to dry loose sediments. Further, they rarely found subsequent PM_{10} concentrations in the wind tunnel that exceeded 100 $\mu g/m^3$, a level allowable by National Ambient Air Quality Standards (NAAQS), although still exceeding California air quality requirements. Large droplets from high-intensity precipitation events and sprinklers are highly effective at forming physical soil crusts (Fang et al., 2007; Wu and Fan, 2002).

Additional study of salinity issues would inform understanding of the long-term sustainability of these potential DCMs. Researchers could also examine the role of precision surface wetting as a temporary DCM for vegetation that takes longer than 3 years to reach full performance.

Artificial Roughness Elements

Artificial roughness as a DCM is divided into four types: solid natural, porous natural, solid engineered, and porous engineered. The mechanistic basis for the ability of artificial roughness to control dust is common among the four types. Roughness elements (either natural or artificial) can reduce the effect of the wind's ability to move sediment on the surface and, therefore, emit dust. Roughness elements protect the surface from dust emission through several mechanisms (Wolfe and Nickling, 1993, 1996). First, the area directly underneath the roughness is generally protected from the force of the wind by the roughness itself. Second, the roughness elements extract momentum from the air. In doing so, they create wakes of relatively low shear stress in which it is more difficult for the wind to exceed the threshold shear stress for particle entrainment (Okin, 2008; Walter et al., 2012). Third, roughness and the wakes produced by roughness trap moving sediment, thus protecting it from additional transport (Raupach et al., 2001).

The material that makes up the roughness does not, in and of itself, matter, and therefore identical roughness elements made of different materials will behave identically. Thus, whether the roughness is natural or engineered is irrelevant. However, the porosity of roughness matters considerably for its behavior. Solid roughness acts as a bluff body, forcing the airstream to go around the object. This leads to acceleration of the airstream around the object, which leads to greater shear stresses at the sides of the roughness (e.g., Walter et al., 2012). In turn, scouring around sparsely arrayed individual roughness elements can occur (Nickling and McKenna-Neuman, 1995). In contrast, turbulent flow that develops within porous roughness elements more effectively removes momentum from the airstream, with the depression of wake-zone shear stress being related to optical porosity (Cheng et al., 2018). Flowthrough porous roughness, in addition, contributes to the capture of particles (Raupach et al., 2001) and reduction of scour on the sides of individual roughness elements (Walter et al., 2012).

Performance

Solid natural roughness. The only type of artificial roughness that has been implemented at a large scale in the Owens Lake area is in the Keeler Dunes area, where straw bales are used as solid natural roughness elements (see Box 4-2 and Figure 4-10). The District reports that 92 percent sediment transport control efficiency was achieved in the center of the array (Gillies and Green, 2014; Holder, 2019b). In the small-scale (1.2-acre) pilot test (Gillies

Box 4-2
Keeler Dunes

The District has experimented with the use of straw bales to stabilize the Keeler Dunes since 2013 (see Figure A). A test area of 100 m × 50 m on the Keeler Dunes was populated with 527 straw bales (resulting in a bale density of approximately 0.1/square meter). The straw bales were placed in an array to replicate natural vegetation patterns, with the bales oriented toward 326° azimuth, so that they present their widest side to the prevailing north and south winds in the valley (Gillies and Green, 2014).

The panel observed several issues on its visit to the Keeler Dunes Area in July 2019. First, the scouring around the bales likely reduced the effectiveness of transport and destabilized the bales. Where two bales were stacked, this scouring led, in some cases, to the toppling of the stack. In addition, toward the edge of the experimental area, large rates of horizontal sand transport led to the burial of bales, negating their usefulness as roughness elements. The eventual breakdown of the bales would eventually reduce their efficiency as a DCM. However, long-term dust control could be possible because the natural solid roughness elements provided the opportunity for plant establishment. In this component of the experiment, native shrub species were planted on the lee side of straw bales. Though these shrubs required hand watering several times per year, it was clear that several had flourished in their locations. Others, however, had succumbed to scouring or burial at the lee side of bales.

FIGURE A Use of solid natural roughness elements at the Keeler Dunes.
SOURCE: Photo courtesy of David Allen, panel member.

FIGURE 4-10 Test of engineered solid roughness elements at Owens Lake.
SOURCE: Holder, 2019d.

and Green, 2014), the overall control efficiency was considerably less because this control efficiency was not attained throughout the treatment. This result is due to the large spatial scale over which transport control becomes effective; sediment transport control efficiency is not achieved until some distance from the edge of the area where the roughness elements are deployed (at a normalized distance downwind [NDD; the distance downwind divided by the height of the roughness element] of about 100 NDD or about 40 m [131 feet] with 40-cm [15.7 feet] high bales). Similar edge effects occur in managed vegetation sites as well, if the sites are not bounded by other measures that reduce near-surface wind velocities. Scouring/burial can also reduce the effectiveness of the roughness elements as DCMs.

Solid engineered roughness. All things being equal, solid engineered roughness elements (see Figure 4-10) would likely perform the same as solid natural roughness elements. In the short-term experimental work done in 2014 (T1A-4) and 2015-2016 (T26), control efficiency of 90 percent was achieved in the center of the array (~160 NDD, ~60 m from the edge of the array), though the distance over which control efficiency is obtained depends on the density and distribution of roughness elements (Gillies et al., 2017, 2018a).

FIGURE 4-11 Testing of engineered porous roughness elements at Mono Lake.
SOURCE: Holder, 2019c.

Porous roughness. Only limited testing has been done with porous roughness elements (see Figure 4-11), and never at Owens Lake. Porous engineered roughness elements were investigated in wind tunnel tests and at Mono Lake in 2017-2018. The results of these tests confirm that porous engineered roughness elements attain target control efficiencies over shorter distances than solid roughness elements (~70 NDD for porous roughness elements and ~140 for solid roughness elements) (Gillies et al., 2017, 2018b).

No testing has been done with porous natural roughness elements (e.g., brush piles, or "vertical mulch"), but this approach could combine the positive features of the other approaches without many of the negative effects. For instance, as porous elements, they would likely attain target control efficiency at shorter distances from the edge compared to solid natural roughness elements and would also reduce the amount of scouring and burial induced by individual roughness elements.

Practical Considerations

The use of roughness elements made of natural materials holds some promise as a way to promote establishment of native shrub communities. In addition to protecting the plants from abrasion and reducing the overall level of horizontal flux, the eventual breakdown of the natural material would add organic matter to the soil, resulting in improved soil water-holding capacity, supporting plant growth and therefore providing the potential for the DCM to be self-sustaining.

An additional benefit of solid natural roughness elements as a DCM is that they could be deployed rapidly, and reversibly, as an emergency measure should a BACM fail. The material from which the roughness elements are made would determine their longevity in the Owens Lake environment.

Water Use

No additional water is required to support artificial roughness as a DCM, unless establishment of vegetation is a specific goal of the project to enhance longevity of the control. At Keeler Dunes, water use was 0.1 ft/year during establishment of vegetation (Holder, 2019c).

Environmental Implications

Artificial roughness can serve as nurse sites for native shrubs, which enhance the habitat for small mammals and other native animals. Because of their lower density, porous roughness elements would likely be better sites for native shrub establishment (probably only if the shrubs are occasionally artificially watered). Porous natural roughness elements would also provide habitat for native animals. Although weed/seed-free bales were used at Keeler Dunes, straw bales raise concerns about the introduction of unwanted species.

Through decomposition, natural roughness elements would likely contribute to soil organic matter development and increase soil water-holding capacity, especially on sands. Depending on their source material, engineered artificial roughness elements would not, in all likelihood, contribute to soil water-holding capacity as they degraded; rather, they would contribute to pollution by plastic particles of all sizes.

The aesthetics of artificial roughness elements is a downside, although some effort can be made to mimic natural vegetation distribution.

Energy Use

Artificial roughness is a relatively low-energy DCM. Energy use in artificial roughness is associated with the production and transport of the roughness materials. Engineered roughness elements would have higher energy use associated with their production compared to natural roughness.

Cost

The capital costs of the Keeler Dunes project were $52 million/square mile with plantings included and $9 million/square mile without. Annual operating costs without plants are minimal (estimated at ~$230,000/year based on the costs of gravel BACM), and with periodic watering of the plants operating costs are $1.1 million/square mile. The capital costs of engineered roughness are estimated at $64 million/square mile and $45 million/square mile for porous and solid, respectively (Gillies et al., 2017; Holder, 2019c,d). No estimates are available for installation costs for natural porous roughness.

Information Needs to Inform Decision Making

The lack of testing of natural porous roughness on the lakebed, especially in places where vegetation has the potential to be regenerated, is a major gap in our understanding of the potential for artificial roughness to contribute to dust control.

Shrubs: Modification of Managed Vegetation BACM Coverage Requirements

Shrub communities composed of several salt-tolerant shrub species are commonly found on the Owens Lake playa surface as well as the surrounding bajadas above the regulatory shoreline. Native plant communities stabilize otherwise erodible surfaces by reducing the wind speed at the surface, filtering entrained sediments through the canopy, and by biotic factors including root mass and shedding of biomass on the surface under the canopies. The current vegetation cover BACM requires a minimum of 37 percent vegetation cover, with additional spatial distribution requirements, to produce an estimated 99 percent dust control efficiency. The original experiments and existing vegetation plantings for dust control on Owens Lake use saltgrass. However, with the addition of more native species to the approved vegetation list, the potential for the use of shrubs as a DCM has arisen. LADWP has proposed to test whether similar control efficiencies could be obtained using shrubs with lower percent vegetation cover and water use.

The mechanisms by which vegetation reduces aeolian transport, and therefore dust emission, are the same as those described for artificial roughness. Low-lying vegetation, such as saltgrass, mainly protects the surface by directly covering the surface, thus reducing the available area for particle entrainment, and by trapping saltating material that has been entrained from the remaining bare areas. The wake area with reduced surface shear stress in the lee of shrubs protects larger areas from emission, more efficiently removes momentum from the wind, and captures more (and higher) airborne material (e.g., Raupach, 2001). Thus, there is merit to the notion that the same amount of control efficiency might be obtained with lower vegetation cover if taller plants (e.g., shrubs) were used in managed vegetation areas.

Shrubs can also provide other unique ways of addressing existing challenges to managed vegetation cover in Owens Lake. Greasewood (*Sarcobatus vermiculatus*) and Parry's saltbush (*Atriplex parryi)* dominate the alkaline soils, and *Atriplex confertifolia* can occur in both well-drained alluvial fans, and poorly drained alkaline basins (LADWP, 2010; Smith, 2000). These woody shrubs have deeper roots and in the portions of the lakebed with deeper freshwater, they may be able to access this water, once they are mature. Woody species have been used in other semi-arid systems to lower the groundwater table and prevent saline groundwater from intruding into rooting zones (Bell et al., 1990), which would be an important tool if it is possible with the species and conditions at Owens Lake.

Performance

To date, no direct measurement of the control efficiency of shrubs on Owens Lake has occurred. Nonetheless, lessons from other tests can be drawn. In the Keeler Dunes Dust Control Project site, control efficiencies of 85-92 percent were attained in the center of the array of straw bales and vegetation plantings (Gillies and Green, 2014; see Box 4-2). Theoretical considerations as well as tests sponsored by the District indicate that porous roughness elements, such as shrubs, may be more effective than the solid roughness elements used at Keeler Dunes

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

(Gillies et al., 2017; Holder, 2019c). However, the effect of roughness depends on the density of the roughness and the distance from the edge of the roughness array.[11]

A shrub-based managed vegetation BACM, with shrub densities of ~0.2 per square meter (0.17 per square yard),[12] or roughly 10 percent cover, should have greater than 85 percent control efficiency within 25 meters of the edge of the shrub area. It has not been tested whether greater than 95 percent or 99 percent control efficiency can be obtained, although preliminary simulations assuming porous vegetation estimate that greater than 20 percent shrub cover may be required (see Box 4-3).

Practical Considerations

Because of edge effects applicable to any DCM based on roughness elements, relatively large areas (>10 ha [24.7 acres]) should be used so that the majority of the area is within target control efficiencies. Initially, shrubs planted at the correct density, but as smaller individuals, will not be able to provide this control efficiency. It may take 5-10 years for nursery shrubs to grow into mature plantings, depending on the species, and thus additional DCMs will be required while shrub stands are being established. If shrub densities are too low, they might become unsustainable, because pedestaling and abrasion of shrubs by moving sand can cause dieback and mortality (Okin et al., 2006).

Water Use

The Keeler Dunes site uses ~0.1 ft/year for shrub densities one-half of that which would be required for 99 percent control efficiency. Therefore, beyond initial watering and leaching (0.1-7.9 ft/year, using values from the managed vegetation BACM), at least 0.2 ft/year would be required during the growth phase (assuming a plant density twice that of the Keeler Dunes). The maximum plant size and plant density will depend on additional factors such as soil texture and salinity. If vegetation is used during the establishment and growth phase to fill gaps between small shrubs, additional watering will be required. After shrubs have been established and have grown to target sizes, watering could be tapered to zero, because shrubs should be able to survive on local rainfall. However, watering infrastructure for management of prolonged drought should be considered.

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[11] Regarding density, use of the calculations of Gillies and Green (2014; Equation 1) suggests that doubling the density (all other things being equal) should reduce flux by 73 percent; increasing roughness density by 50 percent is expected to reduce the flux by 53 percent. Regarding edge effects, Gillies and Green (2014) estimate that a 1-ha area (100 m × 100 m [2.5 acres]) would have approximately 25 percent of the area with greater than 85 percent control efficiency, and a square 10-ha area would have approximately 92 percent of the area with greater than 85 percent control efficiency (85 percent was the revised target control efficiency for this project).

[12] This density is assumed to estimate control efficiency from the Keeler Dune data, based on the fact that two shrubs are roughly equivalent to one straw bale. Shrubs are roughly the same height as the ~40-cm (1.3-feet) high bales, but approximately one-half the width of the 110-cm (3.6-feet) wide bales, and thus have a profile area of approximately one-half of the bales used on Keeler Dunes. See Gillies and Green (2014) equation 2.

Environmental Implications

Shrubs have the potential to provide considerable habitat for native and migratory species. Of the habitats at Owens Lake, shrublands support the most diverse species of lizards and snakes, as well as additional birds and mammals that are not supported by other habitats (LADWP, 2010). Shrubs have also been accepted as a way to reduce aeolian transport in environmentally sensitive areas, though required watering infrastructure is a potential limitation to the establishment of new shrubs in these areas. Shrubs also have positive aesthetic value.

Energy Use

If sited appropriately and groundwater pumping is not required, energy use for shrubs is expected to be low.

Systemwide Issues

Because of salt sensitivity, shrubs are most appropriately sited along the sandier margins of the Owens Lake bed. Edge effects would be reduced if located adjacent to DCMs that also reduce near-surface wind velocities.

Information Needs to Inform Decision Making

Large, established, relatively dense shrub stands could reduce aeolian transport and dust emission from the Owens Lake bed, but their potential to attain 95 or 99 percent control efficiency has yet to be established. Additional research is needed to document the vegetated cover associated with target control efficiencies using shrubs. Further study could also determine whether specific species are more appropriate for different lake conditions, such as depth to groundwater and salinity. Research could also examine whether shrubs could be used to lower the shallow groundwater table in saline areas of the lake, and thereby improve conditions for other managed vegetation.

Cobbles

As a zero-water use control measure, cobbles are similar in nature to gravel, except their size is larger, on average, and not as uniform as gravel, with individual grains ranging from 2.5 to 10 inches (6.4 to 260 cm). Cobbles and larger-sized boulders are now used as part of the Owens Lake Land Art Project (and in an unplanned fashion, on the sides of the access roads on the lake) (see Figure 4-12). The mechanism by which cobbles could control dust emissions is similar to gravel, by substantially reducing the capillary rise of saline groundwater and salt efflorescence to the surface while also preventing wind erosion of the surface underneath. The nooks and crannies present in non-uniform cobble have a greater capacity for capture and storage of windborne material compared to the more-uniform gravel.

Box 4-3
Modeling Shrub Density Requirements

LADWP proposes to test the possibility of a new managed vegetation BACM (or a revision to the existing managed vegetation BACM) utilizing shrubs instead of grasses, which are currently used successfully as a BACM on the lakebed. To this end, LADWP plans to test a model of saltation flux at several sites to calibrate and validate it for the lakebed, and then use the validated model to develop performance requirements for a new shrub BACM. This model would serve as the basis for a proposal for a new (or modified) BACM.

LADWP has proposed the Okin (2008) model of shear stress partitioning as the basis for this approach. The Okin model provides a reasonable basis for this analysis. However, some simple modeling using the Okin model and 5-minute winds from North Beach sheds light on the amount of vegetation cover that may be needed for 99 percent control efficiency. Using simple assumptions about vegetation size (0.5 m diameter) and aspect ratio (1), the model predicts that 25 percent shrub cover would provide ~99 percent control efficiency using the parameters in Li et al. (2013) for the Shao et al. (1993) saltation flux equation. Using more conservative parameters from Mayaud et al. (2017), the model predicts that 38 percent cover shrub cover is required for 99 percent control efficiency. To obtain 95 percent control efficiency, 13 and 18 percent cover are required for the Li et al. (2013) and Mayaud et al. (2017) parameters, respectively (see Figure A).

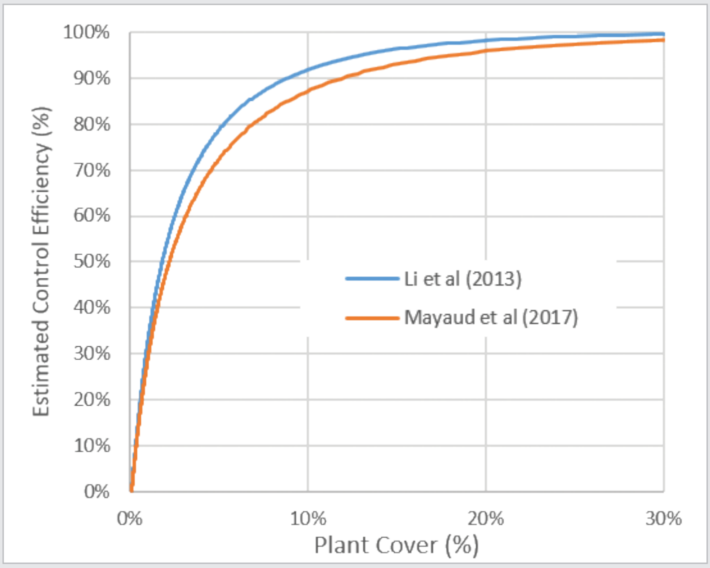

FIGURE A Estimated control efficiency (CE) using two sets of parameters in the Okin (2008) model using 5-minute winds from North Beach, assuming gamma distribution of plant spacing and plant height = plant diameter = 50 cm.

At these densities, biological constraints on the sustainable densities of rainfed shrubs need to be considered. Typical existing shrub communities on the basin floor have shrub covers of approximately 23 percent (see Figure B). Existing shrub communities likely established when groundwater pumping caused the disappearance of groundwater-dependent alkali meadows and the establishment of shrub communities that do not depend on groundwater. Thus, whether solely rain-dependent communities can be established on the lakebed with densities sufficient to obtain 99 percent control efficiency is an outstanding question. It appears possible, however, that a rain-dependent shrub community could provide at least 95 percent control efficiency if vegetation cover exceeds 20 percent. In a managed vegetation BACM, irrigation may be able to increase vegetation cover (and size) beyond the threshold required for 99 percent control efficiency.

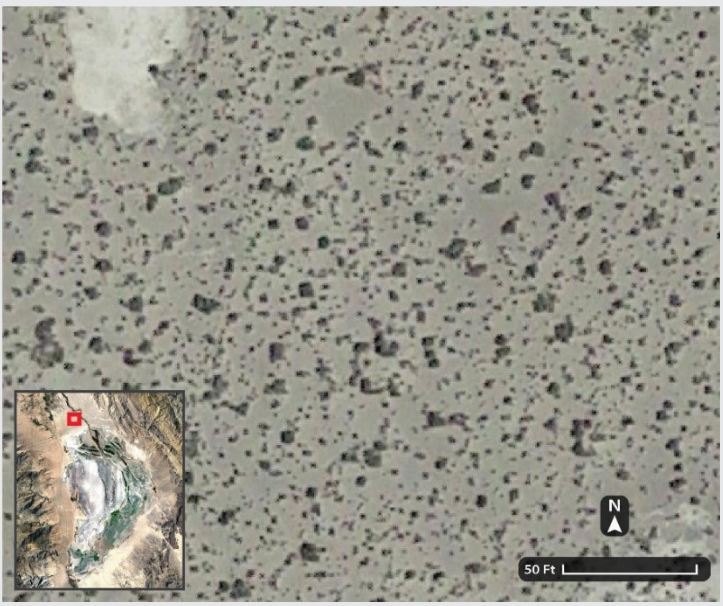

FIGURE B Screen shot of Google Earth image of a shrubland north of Owens Lake (centered approximately at 36°33'20.9"N 118°00'35.9"W) used to analyze existing shrub cover.
NOTE: Vegetation cover in this image is approximately 23 percent.

FIGURE 4-12 Use of cobbles and boulders at Owens Lake as part of the Land Art Project, with cobbles used along trails to provide enhanced public access. The cobbles trap seeds and sand, providing sites for the establishment of native vegetation.
SOURCE: Photo courtesy of Valerie Eviner, panel member.

The performance and lifespan of cobbles have not been characterized, although expected to be similar to gravel. Also similar to gravel, under extreme flooding, cobbles could be displaced, exposing the surface underneath.

Environmental Implications

One noteworthy difference between gravel and cobbles is that the non-uniform spacing between cobbles allows for growth of some vegetation by trapping windblown soil and seeds (see Figure 4-12). Sand and seeds trapped in this way are held above the original, potentially salty, surface, and because of the coarse texture of the windblown sand could have a low capacity for capillary rise of salts. Cobbles on the surface of the soil are similar to "rock mulches" that have been used in dryland agriculture throughout history. By producing still-air void spaces at the surface, cobbles inhibit evaporation from the soil surface, thus increasing the length of time that soil water is available for vegetation. In addition, protected microsites are produced within the uneven surface of a cobbled area. With lower evaporation rates and greater shade than flat surfaces, these microsites have higher potential for germination and establishment of native vegetation. This autogenic regeneration of native vegetation was observed by the panel at the Owens Valley Land Art Project. Thus, beyond directly protecting the soil surface from wind erosion, cobbles can serve as sites of native vegetation regeneration requiring no added water.

Because of their uneven surface, cobbles provide a better habitat for nesting shorebirds when placed adjacent to shallow flooding areas, and they provide shelter for other non-aquatic species, especially if vegetation regeneration has occurred. Aesthetically, cobbles look more natural than gravel because of their non-uniform size and colors and vegetation regeneration. Similar to gravel, emission of various other air pollutants during the mining, transport, and distribution of cobbles and other negative environmental impacts of cobbles mining are of concern.

Energy Use

Energy use associated with cobbles is expected to be similar to that of the gravel BACM, with intense energy usage during mining, transport, site preparation, and distribution of cobbles.

Information Needs to Inform Decision Making

The source of cobbles, the costs and energy use associated with its transport and distribution, and the overall environmental impacts of its implementation are unknown. In addition, the long-term sustainability and maintenance requirements of cobbles for dust control while providing suitable sites for vegetation is unknown.

Sand Fences

Sand fences are vertical barriers used to control movement of windblown sand. The mechanisms for controlling PM_{10} emissions are modifying the airflow, trapping the mobile sand, and reducing fetch. Sand fences are widely used in various environments such as deserts, beaches, and lake and river beds, and several studies report on designs and modeling approaches to optimize design parameters (e.g., array characteristics) and predict their performance (Bruno et al., 2018).

Approximately 19,500 linear feet of sand fences are installed at Owens Lake, primarily in the T1A-1 area covering about 250 acres, a minimum dust control area that enables use of a non-BACM. The installed fences are constructed from ultraviolet light–resistant fabrics with 50 percent porosity and supported on 5 feet tall posts (see Figure 4-13).

FIGURE 4-13 Sand fence at Owens Lake.
SOURCE: Schaaf, 2019.

Performance

In the 1990s, modeling analyses examined the potential for sand fences to provide target control efficiencies at Owens Lake (Ono, 1996; CH2M Hill, 2000). CH2M Hill (2000) found that the fence spacing to achieve 98 percent control efficiency was so close (20 feet for 4-foot fences) that continuous dunes could form, rather than discrete dunes at each fence. Such close spacing required extensive lengths of fencing—250 miles of 4-foot fences per square mile—and would necessitate removal of large volumes of sand as part of maintenance. Straight fences also showed poor performance when wind direction was parallel to the fence (CH2M Hill, 2000).

A Single-Event Wind Erosion Evaluation Program (SWEEP) model was used to determine the optimal spacing of the posts to attain at least a 31 percent removal efficiency (Schaaf, 2019). Eighteen Sensit/Cox Sand Catchers are used to monitor performance, and the control efficiency is determined annually when compared with baseline sand flux data from the pre-dust control period. Although this method does not produce an accurate estimate of PM_{10} control efficiency (see Chapters 2 for details), reported control efficiency values range from 70 to 90 percent over a period of 9 years (Schaaf, 2019). The efficiency has also been reported for three different wind speed ranges, although there is significant variability in the data. The uncertainty in the measurements has not been reported, which is necessary for making reasonable quantitative comparisons or commenting on the trend.

Practical Considerations

Sand fences are relatively easy to install and immediately effective. The time to install is a consideration, and hence their suitability for emergency use depends on how quickly construction can be done. Although sand fences do not achieve BACM-level control efficiencies, they are effective at localized reduction of dust levels. Other advantages include prevention of sand intrusion into gravel-deployed areas and protection of establishing vegetation and the edges of managed vegetation areas from mortality through sand abrasion. The lifespan and durability of the fence depends on the material used, and required maintenance is minimal, especially if durable material is used for fence construction. Routine wear and tear is a consideration, and the fabric may need periodic replacement. Periodically, the trapped sand from the area at the base of the fence will need to be removed.

Water Use

There is no water use associated with sand fences.

Environmental Implications

Sand fences can provide perching sites for birds that predate on the Snowy Plover, such as raptors and ravens. For sand fences within 0.25 miles of occupied shorebird nesting habitat, LADWP (2010) requires designs of posts and fencing that deter perching by predator birds. Sand fences also serve as a barrier to movement of wildlife migration. At Owens Lake, creation of a gap at the base of the fence and burrows and passages at intermediate locations in the fence has helped alleviate this problem. Nevertheless, sand fences should not be used in core wildlife areas. In addition, sand fences have poor aesthetic value on the lakebed.

Cost

The current installation cost of sand fences (based on 31 percent control efficiency) is approximately $15 million/square mile. Annual operating costs, including fencing repairs, are estimated to be $600,000/square mile (Valenzuela, 2019b, 2020b). The infrastructure is anticipated to last for 5 years before replacement is needed.

CH2M Hill (2000) estimated that 95 percent control efficiency would cost $48 million per square mile and $700,000 per year in maintenance (adjusted to 2019 dollars).

Solar Panels

Solar panels (photovoltaics, or PV) have been proposed, and tested, as a potential DCM. Solar panels would control dust by reducing ground-level wind speeds (Ravikumar and Sinha, 2017). As tested at Owens Lake (2014-2017; see Figure 4-14), the panels were placed on top of gravel, a BACM discussed previously in this chapter. However, the use with non-gravel (e.g., vegetated) surfaces could be explored because panel cleaning would provide small amounts of water, and recent studies have found that the shading can enhance some plant growth (Jossi, 2018). Three different ballast configurations and two perimeter barrier configurations were examined in the field test.

FIGURE 4-14 Solar panel testing installed on gravel at Owens Lake using pile-driven mounts (top) and squat ballast mounts (bottom).
SOURCE: Schaaf, 2019.

Performance

Initial wind tunnel testing suggested the potential for BACM-level control efficiencies, reducing ground-level wind speeds. However, in the field tests at Owens Lake, the solar panels were not found to reduce ground-level winds as much as desired, although no sand flux measurements were taken (Schaaf, 2019). It is not apparent how closely the tested configurations match those in utility-scale PV installations or to what degree those configurations could be altered to further reduce wind speed at the surface. Installation over non-gravel surfaces was not tested. An impediment to conducting a more thorough analysis of the potential of solar panel arrays as a control measure is the apparent lack of formal reports documenting the testing of the three panel configurations during 2014-2017.

Practical Considerations

Solar panels have the potential to beneficially use the open space over the lake, providing electricity, while also controlling dust emissions. The Owens Lake area has a high potential for producing solar power (Bolinger and Seel, 2018).[13] The presence of other solar panel farms in the region is suggestive that a solar farm could be economically attractive.

Water Use

The solar panels themselves would require little water. Assuming 26 gal/megawatt hour (MWhr; Klise et al., 2013) and 54,000 MWhr/km^2·year (NREL calculator[14]), the estimated operational water requirement is about 0.02 ft/year. Peak water use was found to be about 50 times annual operational needs for two locations in southern California, primarily for dust control during construction (Klise et al., 2013), leading to an estimate of roughly 1 ft during installation. How these translate to a project at Owens Lake requires investigation.

Environmental Implications

The habitat value of an area of solar panels largely depends on the substrate underneath. The use of gravel provides poor-quality habitat. If the solar panels are placed directly on the natural lakebed, particularly at higher elevations where vegetation growth is feasible without underdrains, the solar panels could enhance plant growth. However, the Multiagency Avian-Solar Conservation Working Group (2018) noted that the risk of injury or mortality to birds through collision and electrocution from transmission lines needs more study. Hernandez et al. (2015) suggest avoiding solar panel use near important conservation areas, particularly because of habitat fragmentation, which may be less of an issue over Owens Lake because

[13] See https://atb.nrel.gov/electricity/2019/index.html?t=su#jkwhhtv7 (accessed January 28, 2020).
[14] See https://pvwatts.nrel.gov/pvwatts.php (accessed January 28, 2020).

current dust control applications are of a fractured nature. Extensive application of PV panels should consider such potential ecological effects.

A potential disadvantage of solar panels is aesthetics, although how they compare with bare gravel or other BACMs is not apparent. Some recent solar panel installations have used creative approaches to improve the aesthetics of solar farms. The solar panels could be designed to look like a water surface, but this aesthetic could harm birds. Because of extensive disruption to the surface, solar panels are not appropriate for environmentally sensitive areas.

Energy Use

Solar panels offer the potential to provide a long-term renewable energy source. Wu et al. (2019) estimate that the power production from 1 square mile of land would be 77 MW. Increased PV efficiencies would lead to increased power production per acre. Energy use is associated with production of the materials, transport to the site, and installation.

Costs

Capital costs for both fixed tilt and tracking solar panels in 2018 were highly variable, averaging slightly more than $1-$1.6 per watt (direct current) installed, and have been falling (Bolinger and Seel, 2018).[15] Assuming power capacity of 77 MW/square mile, the cost of installation is estimated between $77 million/square mile to $120 million/square mile. These costs are in addition to those for any underlying surface preparation. Bolinger and Steel find a mean operating cost of about $8/MWhr. Such large capital and operating costs dwarf the estimated costs of other BACMs, although solar panels provide a long-term source of revenue. Using the NREL calculator, a 77 MW (about 1 square mile) plant in the Keeler area would generate approximately $22 million annually.

Installation lifetimes for utility-scale PV farms are about 25-40 years.[16] A more comprehensive economic evaluation of the actual likely capital and operating costs, as well as potential benefits, including how this fits into California's renewable energy plans, would inform future evaluation of the use of solar panel farms as a potential BACM when considering aesthetics and other factors.

Information Needs to Inform Decision Making

Knowledge of how solar panels fit within an integrated management plan for the Owens Lake area would benefit from more detailed information on control effectiveness (without gravel) as well as environmental and economic assessments. A potential approach to assessing

[15] See https://atb.nrel.gov/electricity/2019/index.html?t=su (accessed January 28, 2020).
[16] See https://www.nrel.gov/analysis/tech-footprint.html (accessed January 28, 2020).

how a large-scale PV installation would impact ground-level wind velocities and dust generation would be to conduct tests at current PV facilities in the area. Tests could also assess the potential for panel extensions, which are designed to reduce the open space below the solar panel, and alternative panel designs to reduce near-surface wind velocities. Examination of how other large-scale installations have impacted local ecology might also inform potential ecological benefits and disbenefits in a similar application to the Owens Lake area.

DUST CONTROL MEASURES NOT EVALUATED IN DETAIL

Two DCMs were not evaluated in detail: chemical stabilizers and biocrusts. Although these are low-water-use or waterless DCMs, they were not evaluated in detail because their potential near-term applicability at Owens Lake appeared limited, either based on acceptability by regulatory agencies or available science. It is possible that new science could emerge in the future that would support for their future use.

Biocrusts

In arid and semi-arid ecosystems across the world, biological soil crusts are critical in stabilizing surface soils and in providing important ecosystem services such as nitrogen addition and moisture retention (Belnap and Lange, 2003). Biocrust refers to a diverse set of communities, with composition depending on environmental conditions. Cyanobacteria, green algae, lichens, mosses, and microfungi are the key components of biocrusts.

In dry alkali environments, such as the Owens Lake playa, cyanobacteria dominate (Belnap and Lange, 2003). Their presence has been observed in the "barren" areas of the Owens Lake playa (LADWP, 2010). Some cyanobacteria are filamentous, and in well-developed mature crusts, they play an important role in the stabilization of the top 3 mm (0.1 inches) of soil. However, biocrusts are also extremely sensitive to disturbances such as compaction (e.g., vehicle traffic, footsteps) and to sand blasting (Belnap and Gillette, 1998). Once disrupted, they show extremely slow recovery (Chiquoine et al., 2016), particularly on sandy soils (Chock et al., 2019), where they show little recovery even after 5 years. As they recover, the surfaces they cover are 2-30 times more vulnerable to wind erosion, even after a year of recovery (Belnap and Gillette, 1998). Restoration of disturbed crusts can be difficult, with only a portion of the community being cultivatable and uncertain performance of cultivars under field conditions. They have high variation in establishment, and a long recovery time, during which they are vulnerable to sand blasting (Chiquoine et al., 2016). Thus, these are unlikely candidates for dust control on their own, particularly over the short term. However, if areas of Owens Lake are undisturbed over the long term, and receive little sand movement, these crusts could become an important part of the ecosystem and dust control, as they are across arid regions of the world. Biocrusts have been considered as a potential DCM for environmentally sensitive areas, although more research would be needed to define the conditions necessary to provide reliable dust control and whether such conditions could be sustained at Owens Lake.

Soil Binders

Soil binders are chemicals applied to stabilize the soil surface and prevent dust emissions. Soil binders require no water, other than the water required to apply the chemicals. Although shown to be effective elsewhere under certain conditions (Bolander, 1997; Giummarra et al., 1997), there are concerns about their durability at Owens Lake. Only a thin layer at the top of the soil surface is controlled, which could be abraded and fail during high wind events, potentially leading to large emissions. Use of soil binders would require careful monitoring of the integrity of the surface. A small-scale field test using soil binders was conducted in 2013, but the results were compromised by a flood event. A second, larger study was designed to test eight different chemical stabilizers, but the study has yet to be conducted and is awaiting approval from the California Department of Fish and Wildlife (Schaaf, 2019; LADWP, 2020b). The California State Lands Commission has previously stated that chemical stabilizers are not acceptable on the lakebed because they are not consistent with public trust values (GBUAPCD, 1994).

MONITORING BACM EFFECTIVENESS

To ensure that deployed BACMs and other DCMs maintain their required emission control effectiveness, surrogate metrics (performance standards or criteria) are relied upon instead of direct estimates of PM_{10} (see Table 4-2). Performance standards are set to ensure that approved BACMs reach the required control efficiencies based on data collected for this purpose during the BACM testing and approval phases. Thus, performance standards serve as measurable surrogates for a BACM's ability to attain required control efficiencies (e.g., 99 percent reduction in dust emission) based on previous testing and do not directly represent a BACM's in situ attainment of required PM_{10} control efficiencies. Performance standards are tailored to individual BACMs and can comprise measurements of sand flux (e.g., brine BACM, tillage with flooding backup), ridge spacing and height (tillage), area of standing water or surface-saturated soil (shallow flooding BACM), vegetation cover (managed vegetation BACM), or induced particle emission (dynamic water management, tillage), among others. Direct PM_{10} monitoring is an established performance standard for only one BACM (tillage; see Table 4-2).

Those surrogate measures do not capture the different dust control effectiveness levels that might result from variations in the implementation of DCMs. For example, in shallow flooding for dust control, at least 75 percent of the surface must be wet or have saturated soil. However, this performance requirement does not explicitly account for the differences in dust control that might occur between a patchwork of shallow flooding amounting to 75 percent coverage and a continuous coverage amounting to 75 percent of the dust control area. Similarly, in the managed vegetation DCM, the areal coverage of the vegetation must be at least 37 percent of the dust control area. This performance requirement does not explicitly account for the differences in dust control that might occur with different plant groupings and different maturities and heights of the vegetation. These variations in implementation create uncertainties in the degree of actual dust control that might be achieved, although they might adhere to the surrogate metric.

Uncertainties in determining DCM effectiveness at the 99 percent level based on the current measurement approaches have not been characterized. The difference between 98.5 percent and 99.5 percent control is a factor of three in emissions, and such accuracy in measuring DCM effectiveness is critical when developing an overall strategy that requires reduction of PM_{10} emissions by 99 percent (see Chapter 2).

Requirements for Developing Alternatives to Existing BACMs

The District enforces the requirements of the SIPs through continual oversight of LADWP's dust control strategy using stipulated test methods and performance standards to determine compliance. As of 2019, on the emissive lakebed itself, nearly all emissive areas have experienced BACM implementation (with the exception of some environmentally sensitive areas), a fact that is reflected in the already high degree of dust control on the lakebed. Transitions from one BACM to another are possible, but LADWP is required to maintain PM_{10} control during such transitions (Board Order 160413-01 Paragraph 13). Transition from one existing BACM to another without meeting the performance standards of either BACM may be done, but is limited to an area with maximum size of 3 square miles at one time (Board Order 160413-01 Paragraph 13.C).[17]

LADWP may request, in writing to the District, the establishment of alternative DCMs as approved BACMs for use on Owens Lake. This process involves a planning phase in which the DCM's feasibility is determined, considering criteria such as environmental impact, public trust value, climate change, risk, aesthetics, and compliance with existing laws and regulations. If the proposed BACM proves feasible, then meetings are held to introduce the concept to and obtain feedback from stakeholders. Subsequently, a plan is developed for field pilot study of the BACM to establish dust control efficiency relationships over a wide range of climate conditions. Upon receipt of permits and leases from relevant land owners and agencies, including the District, the California Department of Fish and Wildlife, the Lahontan Regional Water

[17] District Governing Board Order #160413-01 Requiring the City of Los Angeles to Undertake Measures to Control PM_{10} Emissions from the Dried Bed of Owens Lake. See https://gbuapcd.org/Docs/District/AirQualityPlans/OwensValley/Board_Order_FINAL_20160425.pdf (accessed January 28, 2020).

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Quality Control Board, the U.S. Army Corps of Engineers, and the California State Lands Commission, the design and construction can begin. A 2-year monitoring phase follows construction in which PM_{10} control performance is measured by District-approved methods. If PM_{10} control is demonstrated, then LADWP and the District's Governing Board may adopt the new BACM. However, further implementation of this new BACM in new areas or transition of existing DCMs to this new BACM may require a similar process (Valenzuela, 2019b).

Testing cannot be conducted on areas currently under approved BACMs, an area comprising nearly all of the emissive sources on the lakebed. LADWP may implement the proposed new control measure on only one-half square mile of the next area to be identified as needing control (as a BACM Contingency Measure) until the U.S. Environmental Protection Agency (EPA) approves the new measure as a BACM. The District's Governing Board may limit the BACM to specific circumstances, such as distance to the shoreline or for specific soil types (Board Order #160413-01, Attachment D, p. 9). Collectively, the requirement that allows application of new DCMs to no more than 3 square miles, and other constraints, limits the timely transition to more integrated lake-wide dust management practices.

Using PM_{10} Emission Estimates to Monitor BACM Effectiveness

Estimating PM_{10} emissions using PM_{10} concentration measurements in individual dust control areas, rather than performance criteria, could reduce uncertainties and allow for more flexibility in assuring compliance with PM_{10} emission reduction requirements. For example, this approach could be used to demonstrate that less vegetation cover, with the locations and groupings of particular plants designed to maximize dust control, could achieve the emission reductions expected from the current 37 percent coverage requirement. This approach could also be used to assess the effectiveness of hybrid DCMs. For example, if vegetative covers fall below a threshold for required control effectiveness, then roughness elements could be added to return to the required dust control effectiveness.

One disadvantage of relying on control area–specific estimates of PM_{10} emissions, based on airborne PM_{10} concentration, is the difficulty in assessing compliance under low to moderate wind conditions. Current surrogate measures for dust control effectiveness, such as areal coverage of shallow flooding or percent vegetative cover, are applied under any wind conditions. However, if the SIP requires a 99 percent emission reduction for a DCM under the high wind-speed conditions assumed for potential NAAQS exceedances, then compliance can only be directly measured under those high wind-speed conditions. If estimates of PM_{10} emissions, based on PM_{10} concentration measurements, are used to evaluate the performance of DCMs, then the control effectiveness as a function of wind speed must be determined. As outlined in this chapter, control effectiveness as a function of wind speed is already being assessed for some DCMs (e.g., precision surface wetting). If done more broadly, compliance can be demonstrated under a variety of wind conditions.

Overall, tying the operational performance of DCMs directly to PM_{10} control effectiveness would provide flexibility to develop innovative and hybrid DCMs and could allow for adaptive responses for areas that experience declines in control efficiency. In addition, this approach would improve the transparency of SIP planning. Better understanding of the relationship between PM_{10} emissions and wind speeds would highlight how differences in the severity of high-wind events could lead to increases or decreases in NAAQS exceedances. Direct estimation of PM_{10} emissions for DCMs in individual dust control areas would also mitigate the uncertainties associated with the use of surrogate metrics for PM_{10} control efficiency.

CONCLUSIONS AND RECOMMENDATIONS

Evaluation of Dust Control Measures

Conclusion: Based on available data, none of the currently approved BACMs or other DCMs has been documented to achieve mandated dust control efficiencies, while reducing water use (compared to shallow flooding) and consistently providing moderate or high habitat values. Many of the DCMs reviewed involved a high level of land disturbance and infrastructure that could impact cultural resources in environmentally sensitive areas.

Conclusion: Of the DCMs reviewed, precision surface wetting, managed vegetation with shrubs, natural porous roughness, and cobbles appear to be promising strategies, individually or in combination, for substantially reducing water use and providing some habitat value. Examples of hybrid DCMs include managed vegetation combined with either artificial roughness elements or precision surface wetting. As mentioned above, the panel did not attempt to judge the acceptability of those DCMs on environmentally sensitive areas, including those with cultural resources.

Recommendation: Additional research on individual and hybrid DCMs should be conducted to develop new approaches that use less water, maximize other environmental benefits, and ensure that DCMs maintain performance over the long term. Specific research topics to inform future decision making at Owens Lake are outlined in this chapter and include the following:

- Strategies for long-term salinity management in shallow flooding and managed vegetation DCMs, including an evaluation of the capacity to maintain target salinities over time;
- Minimum percent coverage needed for alternative vegetation species and mixtures of species as DCMs with the potential to reduce irrigation requirements, and how site-specific conditions on the lakebed impact the performance, durability, and management requirements of those measures;

- Potential for dynamic precision surface wetting to provide effective control in real-time that reduces water use;
- Approaches to enhancing the formation of salt crusts and their long-term stability under a range of conditions;
- Performance and feasibility of cobbles and natural and artificial porous roughness as DCMs on the lakebed and their potential to provide additional vegetated habitat;
- Potential of hybrid DCMs (e.g., precision wetting with vegetation) that may lead to further reductions in water use relative to either DCM measure alone, while increasing habitat value;
- Performance and reliability of current and proposed DCMs under future conditions anticipated from climate change, including longer-term changes in climate and more extreme weather events; and
- PM_{10} control effectiveness for specific DCMs at various wind speeds.

Monitoring BACM Effectiveness

Conclusion: Operational evaluations of BACMs and other DCMs have relied on surrogate performance criteria to monitor PM_{10} control efficiency, which introduces a high degree of uncertainty.

Recommendation: LADWP and the District should evaluate DCM performance based on PM_{10} emissions from dust control areas, estimated from measurements of airborne PM_{10} concentrations under a variety of wind conditions.

5

Addressing Current and Future Management Challenges with a Systems Approach

Chapters 2 and 3 present the complex context of air quality, water resources, and cultural and environmental factors that affect decisions at Owens Lake. Chapter 4 describes many current and potential dust control measures (DCMs), but no single measure meets dust control requirements while substantially reducing water use (compared to the shallow flooding Best Available Control Measure [BACM]) and consistently providing moderate- or high-value habitat on the lakebed. Meeting the broad goals for Owens Lake will instead require an integrated systems approach to dust control. This chapter outlines a systems approach to address current and future challenges.

MANAGEMENT FOR MULTIPLE GOALS

Management goals at Owens Lake have shifted substantially over time, with the evolution of regulations and societal values. In the early 1900s, the water of Owens Valley and Owens Lake was viewed by many as a resource to support the growing city of Los Angeles. The desiccation resulted in the region around the lake having the highest concentrations of particulate matter 10 micrometers or less in diameter (PM_{10}) in the United States. Decades after Owens Lake was drained, the U.S. Environmental Protection Agency (EPA) and California air quality standards mandated dust control efforts. The Los Angeles Department of Water and Power (LADWP) and the Great Basin Unified Air Pollution Control District (the District) developed dust control approaches, which LADWP implemented in phases, each with strict compliance time frames. These dust control efforts have greatly reduced PM_{10} emissions at Owens Lake, although additional progress is needed to meet both federal and state air quality standards (see Chapter 2).

The current dust control approaches are largely engineered approaches, and most require ongoing inputs of energy and resources, such as water or labor rather than the creation of a

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system that is self-sustaining over the long term. Even the managed vegetation BACM was designed as an engineered system—a monoculture that requires perpetual groundwater drainage and irrigation. Now that PM_{10} emissions have been reduced over large portions of the lakebed, LADWP management strategies are evolving toward those that conserve resources, particularly water. Owens Valley water is projected to become an increasingly important portion of LADWP's future water supplies (see Chapter 3).

Shallow flooding, a water-intensive DCM, is used on nearly 30 square miles of Owens Lake, representing 62 percent of the lakebed area that is currently controlled (see Figure 1-4). As discussed in Chapter 3, shallow flooding created extensive habitat for water birds. Owens Lake, is now one of the most important breeding sites in California for the Snowy Plover (Oring et al., 2000) and provides critical habitat for diverse bird species along the Pacific Flyway, hosting more than 100,000 birds during the spring and fall. This development has regional to global conservation implications, because migrant shorebirds rely almost exclusively on saline lakes in the Western United States, which are overexploited for their water. Those bird populations in the Great Basin have decreased by 70 percent since 1973, and population declines are likely to continue because of increasing human water use and climate change. By 2050, it is projected that most Great Basin waterbirds will have lost more than one-half of their habitat to climate change, and their remaining habitat will be less conducive to successful breeding because of shorter inundation seasons and higher-salinity water (Haig et al., 2019). On Owens Lake, the California Department of Fish and Wildlife requires no net loss of aquatic habitat functions, values, and acreage, based on the 2008 dust control areas, and that 1,500 acres (2.3 square miles) be specifically managed to protect shorebirds and the Snowy Plover (LADWP, 2010), underscoring the importance of considering how efforts to reduce water use might affect habitat functions and values.

Other objectives affect lakebed management decisions, such as consistency with public trust values, as determined by the California State Lands Commission, the main landowner. For example, the commission opposed moat and row as a DCM for its unnatural aesthetics that compromised the viewshed.[1] For currently uncontrolled areas, many of the dust control efforts require extensive land disturbance, which could destroy artifacts and landscape features that are important cultural resources for Native American tribes.

Managing for multiple goals is challenging. Even when solely focused on conservation goals, there can be direct tradeoffs in managing different ecosystem services (Raudsepp-Hearre et al., 2010) or in managing species diversity and certain ecosystem services (Chan et al., 2006). Balancing management for multiple goals can be particularly challenging when optimization of one goal (e.g., diversion of water to Los Angeles) occurs at the

[1] The moat and row DCM does not require the addition of supplemental water to reduce dust emissions from the lakebed. Moat and row consists of an array of earthen berms (rows) about 5 feet high above the lakebed surface with sloping sides, flanked on either side by slope-sided ditches (moats) about 4 feet deep. Sand fences up to 5 feet high are placed on the row tops to increase the effective height of the rows (GBUAPCD, 2008).

expense of another (e.g., shorebird habitat). Management at Owens Lake over the past few decades has been primarily focused on the goal of dust control, which may have inadvertently increased these tradeoffs and limited the ability of the current patchwork of management approaches to address multiple goals. Multiple goals are more effectively achieved when there is deliberate co-management across the goals from the outset (Chan et al., 2006; Fremier et al., 2013; Raudsepp-Hearre et al., 2010). No single dust control approach addresses all management goals and community priorities, but collectively, the goals can best be met lake-wide by coordinating across parcels. This coordination requires project-wide planning that determines where progress toward each goal can be maximized without compromising the progress at adjacent control areas (Chan et al., 2006; Fremier et al., 2013).

By necessity, dust control implementation at Owens Lake occurred in phased projects on strict timelines, rather than through integrated lakebed-wide planning. This lack of lake-wide planning can limit the effectiveness and efficiency of specific DCMs. For example, gravel areas can become emissive following the deposition of dust emitted from adjacent areas (e.g., managed vegetation that is not fully established). As another example, shallow flooding areas can raise levels of saline groundwater in neighboring managed vegetation areas, leading to plant mortality, if not carefully controlled.

Lake-wide planning approaches will become critical with climate changes, as temperature and evaporation rates increase and precipitation becomes more variable, with increased floods and droughts. For example, climate change will make Owens Lake even more important for conservation of shorebirds, but decreased water use for dust control to conserve water resources will necessarily decrease the size of habitat. Lake-wide planning efforts can explicitly identify high-priority locations for water use for habitat management, while targeting the remaining areas as priorities for dust management with decreased water use.

Although large investments have been made in DCMs on Owens Lake to date, an important opportunity for long-term lake-wide planning now exists for several reasons. LADWP's stated objective of decreased water use will necessitate broad-scale changes and integrated planning across multiple goals. In addition, infrastructure is aging and may soon require replacement. Now that many previously emissive areas are meeting dust control requirements, the opportunity exists to conduct lake-wide planning that could reduce water use and improve long-term outcomes. An integrated landscape-based planning approach can take into consideration and take advantage of the recognized spatial variability of the soil textures, depth to shallow groundwater, and salinity, among other factors, to enhance dust control operations. This integrative landscape approach would also reduce maintenance requirements and costs by siting DCMs where they are most appropriate on the lakebed, taking advantage of the most suitable hydrology, soil, groundwater depth, and salinity for specific dust control strategies.

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WHAT IS A SYSTEMS APPROACH?

Ecosystem and landscape ecology provide key principles for ecosystem management that are relevant to the development of a long-term systems approach for dust control at Owens Lake, particularly when balancing the multiple objectives of dust control, habitat creation and conservation, and reduced water use. The key components include the following (Biggs et al., 2012; CBD, 2004; Chapin et al., 2009; Christensen et al., 1996; Clark and Jupiter, 2010; Dale et al., 2000; Seastedt et al., 2008):

- Management of multiple goals, with explicit recognition of tradeoffs and synergies across multiple goals;
- Understanding of the key factors that contribute to each goal, with long-term planning and management focused on developing self-maintenance of these factors, where feasible;
- Adoption of suitable goals and practices based on local conditions;
- Management at the scale/size of the processes that control management goals, and consideration of the landscape configuration of patch types;
- Consideration of temporal scale and variations; and
- Management for resilience.

In the sections below, each of the principles is discussed, including how each can be addressed at Owens Lake as part of a lake-wide, integrated dust management approach.

Management of Multiple Goals

Balancing multiple goals at Owens Lake (e.g., goals related to dust emissions, habitat provisioning, water use, and protection of cultural resources and the viewshed), particularly under a changing climate and decreased water availability, warrants an integrative systems approach to minimize tradeoffs. At the level of an individual dust control area, decreases in water use will necessarily compromise the specific habitat provided by that water. However, the broad ecological effects can be minimized, if water use on the lakebed is prioritized toward sustaining the most valuable, regionally rare habitat, allowing reductions in water use for dust control on other areas of the lakebed.

Development of an integrative, long-term strategy for dust control that meets multiple goals while reducing tradeoffs necessitates an assessment of various dust control configurations as a lake-wide system. Evaluations of alternative configurations should be informed by spatially and temporally explicit priorities, developed through multiple agency and stakeholder collaboration. This process includes identifying priorities that are specific enough to manage. For example, current habitat modeling focuses on habitat for specific bird guilds, without a priority for habitats that are unique along avian flyway corridors or regionally rare.

Roberts et al. (2016) recommends prioritization of management of shorebirds, because their regional conservation is most dependent on the regionally rare habitats provided by Owens Lake.

Systems analysis across multiple goals needs to be supported by a better understanding of the interactions among air quality, wind dynamics, landscape conditions, protection of cultural resources, hydrology, salinity, and the ecology of the system, including the regional significance of habitat types and other ecosystem services in the Owens Valley. Research is also needed on the spatial and temporal factors that affect performance, the effects of adjacent DCMs, and the resilience of various DCMs under a range of conditions (see Chapter 4).

Once a long-term, integrative strategy is developed, it will need to be implemented in phases as DCM infrastructure needs replacement or as opportunities emerge to implement water-conserving measures. Transition of dust control management approaches is currently limited to 3 square miles at any time, which will limit the rate at which more integrated lake-wide dust management can be implemented.

Understanding and Planning for the Key Factors That Affect Attainment of Multiple Goals

A principle of managing for resilient ecosystems is identification of conditions that will fundamentally alter the system and its ability to persist (Biggs et al., 2012; Seastedt et al., 2008). This same principle applies to long-term dust management at Owens Lake, which will benefit from strategies that have the capacity to self-maintain, where possible. As discussed in Chapter 4, long-term salinity accumulations need to be avoided to ensure the continuing performance of managed vegetation sites, and the food webs in the shallow flooding areas that support large bird populations. The effect of climate change on managed vegetation, precision surface wetting, and shallow flooding operations needs to be understood (see Chapter 4), including the effects of higher evaporation rates on water demand and the availability of water supplies to meet that demand under future projected conditions. In a desert landscape where all ecosystems are critically dependent on water, future planning will also necessitate an understanding of the effects of changing water application on Owens Lake habitats and implications within the larger Great Basin ecosystem and beyond. Two examples of understanding thresholds for DCMs are discussed in the following sections.

Shallow Flooding and Its Effects on Avian Habitat

The California Department of Fish and Wildlife requires no net loss of riparian or aquatic habitat functions, values, and acreage, based on the 2008 dust control areas. LADWP must also manage at least 523 acres (0.82 square miles) at Owens Lake for Snowy Plovers and 1,000 acres (1.56 square miles) for shorebirds, in general, because of the importance of saline lake habitat to the conservation of these species throughout the western United States (Haig et al. 2019; LADWP, 2010). A habitat suitability model is used at Owens Lake to assess which specific control areas meet guild-level habitat needs, thus facilitating planning decisions on the depth and areas of flooding and the allowable water salinity of those ponds. The model assesses the suitability of habitat for the different guilds based on salinity, water depth, seasonality/stability of water availability, vegetation, size of dust control area, and microtopography. LADWP is studying habitat suitability, rather than species populations, because bird populations and migrations are affected by many factors that extend far beyond the geographic scope of Owens Lake.

However, assessments of habitat quality based on habitat suitability models are often poorly linked to population health or performance because they fail to consider spatial variation and temporal changes in communities and environmental factors and how individual species react to multiple interacting factors (Seoane et al., 2005; Stauffer, 2002; Tirpak et al., 2009). Shorebirds are diverse, with species differing in salinity tolerance and preferred foraging habitats that range from dry surfaces to deeper ponds, and a guild-wide approach does not necessarily provide habitat for any given species (Roberts et al., 2016). If water use is constrained through natural variability or policy choices, management practices explicitly matched to the conservation needs of priority species are more likely to be successful compared to generic habitat characteristics that do not necessarily support any given species. Expert reviews on the bird Habitat Suitability Model suggested a suite of guidelines for improvement (see Box 5-1). Key recommendations that could provide additional flexibility in Owens Lake dust management decisions include weighting species by their conservation priority (rather than giving each bird guild equal weight), improving assessments of habitat (by including more direct measures of habitat features in both monitoring and modeling), and clarifying the relationship between dust control area size and habitat area.

Self-Sustaining Vegetated Habitat for Dust Control

The majority of Owens Lake is being managed by dust control approaches that are highly engineered. Although they may be effective at dust control, many BACMs require substantial ongoing maintenance, periodic infrastructure replacement, and significant inputs of water (Robinson, 2018). Increased use of self-sustaining systems for dust control would decrease long-term costs associated with energy, water, labor, and materials. DCMs, such as natural artificial roughness and shrubs, could provide habitat with little maintenance or water requirements. Persistence of managed vegetation across the range of lake conditions and in a variable and changing climate necessitates genetic and species diversity. Current efforts at Owens Lake recognize the importance of this approach, because the use of shrubs are being explored and more species and community types have been added to the managed vegetation BACM (see Chapter 4). Consideration of the core needs of managed vegetation includes carefully taking into account the location of managed vegetation, as discussed in the next section.

Box 5-1
Improving Habitat Suitability Models for Owens Lake Management

Expert reviews of the habitat modeling approach at Owens Lake (Roberts et al., 2016; reviews included in Owens Lake Master Plan, 2011) highlight the important contributions of the current model but also stress that current modeling of bird guilds by habitat features is coarse and unable to guide landscape-scale planning, nor can it assess how changes in management or environmental conditions will affect key species. The broad guilds and habitat features used in modeling miss the key environmental drivers, such as salinity thresholds for the algae that support the robust food web (e.g., algae that feed the brine flies, which feed the birds). In addition, the clumping of bird species into guilds glosses over important differences in species needs in terms of food sources, salinity tolerances, water depth for foraging, and habitat/vegetation structure.

Key recommendations of Roberts et al. (2016) for improving the model include the following:

- Improvement of modeling and assessment of habitat needs for the following guilds: Breeding Waterfowl, Breeding Shorebirds, and Diving Water Birds.
- Inclusion of currently unmeasured variables that assess the location of key biological needs and bird behaviors (e.g., foraging versus loafing versus bathing behaviors, invertebrate food sources).
- Avoidance of lumping all conditions into a single habitat score. A lumped score limits the ability to assess whether certain habitat features are degrading or decreasing in area. In addition, a lumped score for an overall guild does not allow for assessment of specific species within the guild, such as those that require different water depths. Lumping across habitat conditions is also misleading because there is unequal confidence and rigor in the current categories used to assign habitat value.
- Improvement of seasonal habitat values, rather than integration of habitat value across the entire year. It is particularly important to focus on summer water availability, which is extremely rare regionally.
- Increased temporal and spatial resolution of monitoring, so that the scale of monitoring matches the scale of the controls over habitat quality and bird distribution. Many current model parameters (such as salinity) are available only as an average over an entire dust control area.
- Clarification of the relationship between dust control area size and habitat area. A linear relationship is assumed (e.g., an area that is twice as large provides twice the habitat) but this needs further assessment.
- Prioritization of which bird guilds (e.g., seabirds) are a management priority, rather than currently weighting all guilds equally, given that Owens Lake has the most potential to provide (and historically provided) habitat for the most salt-tolerant species.

Development of more self-sustaining systems at Owens Lake would likely benefit from more flexibility in regulations. Recently, managed vegetation BACMs that were establishing, but did not meet the targeted percent cover in year 3, were converted to shallow flooding. If these BACMs were sited in areas that were not suitable to their long-term success, conversion to another BACM is the proper decision. However, the short time frame for establishing performance criteria is likely decreasing opportunities to create self-sustaining dust control systems.

Suitable Goals and Practices Based on Local Conditions

A key to successful long-term sustainable management of ecosystems or dust control systems is the setting of goals and approaches that are compatible with the natural conditions of the landscape, considering variability and potential limitations. Managers at Owens Lake have developed a site-specific understanding of which types of management are successful at which types of sites. For example, tillage is more effective in clay soils, which produce clods that are more resistant to erosion. Spatial designs that "let the lake be what it wants to be," with brine pools toward the center and vegetation concentrated along the higher elevation areas, would require lower amounts of water and less intensive drainage and pumping system. Further incorporation of the existing spatial variability and spatial structure of the lakebed conditions, (e.g., depth to groundwater, topography, soils) into dust control design will lead to improvements in dust control efficiencies and reduced costs. Such strategies are essential for the development of long-term self-sustaining systems.

One example of a promising approach is the restoration of native vegetation on the less saline areas of the playa, dunes, and shoreline areas. Although these areas may need initial management to decrease soil salinity, they have low likelihood of continued salt accumulation where groundwater is deep. In these areas, a self-sustaining DCM could be developed by establishing desert shrubs, which are tolerant to low water supply and salinity, and after initial establishment, have relatively low irrigation needs. Other areas may be appropriate for a hybrid of precision surface wetting and vegetation to meet dust control requirements, with much less water use than existing managed vegetation plots.

Selecting practices and goals for a dust control area that are most suitable for local conditions can be achieved by spatially explicit mapping of the key variables that shape a system. The 2010 Habitat Management Plan (LADWP, 2010) provides a clear delineation of seven distinct zones in the lakebed that differ in surface soil, groundwater depth, groundwater salinity, sediment type, surface morphology, and location. It is not clear to what extent the spatial layout of dust management approaches has been guided by these zones, combined with more fine-scale site characteristics and manager knowledge of sites.

A key local condition to consider in any future expansion of dust control is the location of environmentally sensitive areas, particularly areas of cultural significance and those that are likely to contain important artifacts. In a xeric climate, human activity is most likely to be centered upon water sources, although a broad margin of the lakebed will encompass fluctuations in historic lake edges that could contain significant cultural resources. To the extent possible, predictive mapping of likely "hotspots" of currently unidentified areas of cultural significance outside of the current ordered dust control areas could help inform future planning.

Management at the Scale of the Processes That Control Management Goals, Considering Adjacency

The previous section discusses the importance of managing a specific dust control area in a way that best suits local conditions. However, landscape-scale processes (e.g., hydrology, salt accumulation, vegetation spread, decreases in wind speed) are substantially influenced by the size, shape, and configuration of multiple dust control areas across the landscape (Dale et al., 2000). Integrated planning across the extent of Owens Lake will improve the potential to achieve all goals by considering the impacts of adjacent DCMs and the size of the dust control area needed to effectively manage for fundamental processes that control the system, such as groundwater depth, salinity, and wind speed.

More effective and efficient dust control can be achieved by shifting away from the current practice of small-scale patchiness of different types of management across the lakebed (see Figure 1-4) to larger areas of a given management type that are suitable to the location in the lakebed. A small-scale patchwork of dust control approaches that are not coordinated to address issues related to surface water, groundwater, and salinity collectively, will likely lead to DCMs at each patch failing to be as synergistic as possible, because the approaches do not manage those issues on a sufficiently broad scale. For example, long-term sustainability of managed vegetation requires prevention of saline groundwater encroaching into the rooting zone. Sustaining managed vegetation may be more effectively achieved at large scales, compared to having managed vegetation interspersed amid other DCMs that could increase groundwater salinity (e.g., brine pool) or groundwater levels (e.g., shallow flooding) (Scheidlinger, 2008b). Water movement designed to flush salts toward the brine pool over time supports sustainability of the system.

Similarly, DCMs that rely on decreasing surface wind speed, such as managed vegetation and artificial roughness, can result in substantial dust emissions from the windward edges of the dust control area, which receive the brunt of the wind scour. Roughness-based DCMs are more effective when they are large in size and surrounded by other DCMs that decrease wind speed (e.g., managed vegetation, artificial roughness, sand fences, tillage).

The size and nature of neighboring DCMs can also reduce emissions from currently uncontrolled areas. Currently, 1.2 square miles of the total ordered dust control area on the lakebed are uncontrolled, in part due to the presence of cultural resources (see Table 1-1). If the Owens Valley Planning Area continues to be in nonattainment of the National Ambient

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Air Quality Standards (NAAQS) for PM_{10}, DCMs may need to be applied in these areas and could adversely affect artifacts, culturally important sites, and habitat features. Careful selection of dust control approaches on upwind adjacent patches—for example, the use of shrubs or other roughness elements—could decrease wind speeds at the boundary of these uncontrolled areas.

It is also important to consider how management of Owens Lake interacts with the surrounding landscape. In the past, there has been a long-term movement of sand from the lake to off-lake dunes and other areas (Lancaster and McCarley-Holder, 2013; Pavlik, 2008), essentially creating new emissive areas. Although LADWP's mandated dust control efforts are within the regulatory boundaries of the historic lake shoreline, the dust, wind patterns, hydrology, and salt movement are influenced by broader scale processes, and management of emissive sources beyond the lake boundaries are an important consideration for most effective long-term control.

A key challenge to effective management is that the environmental variables and processes that affect progress toward management goals often occur at different scales. Therefore, it is important to match the scale of management and monitoring with the scale of the processes.

Consideration of Temporal Scale and Variability

Critical to the establishment of processes and systems that are designed to be self-sustaining is a realistic time frame. However, that time frame may not match regulatory time frames. The managed vegetation BACM can be risky to implement because vegetation establishment may take longer than the regulatory time frame, especially in dry years. It may take 5 years for mature shrubs to establish (see Chapter 4). Additional temporary DCMs may be needed to manage dust in areas to promote the establishment of plant communities that may be self-sustaining in the long term.

In addition, management approaches that work in the short term may fail in the long term, and awareness of long-term change is necessary. For example, minimizing water use can lead to surface salinity issues over the long term, as salts that inevitably accumulate in a saline basin are not leached over the long term.

Management for Resilience

A resilient ecosystem can maintain itself in response to disturbances, variability, and directional change (e.g., climate change). Particularly in heavily managed novel ecosystems (Biggs et al., 2012; Seastedt et al., 2008), this flexibility can be achieved by many of the core principles discussed in this chapter. As discussed in Chapter 4, however, many information gaps remain about the capacity of current BACMs and potential DCMs to withstand future change.

TOWARD A LONG-TERM, INTEGRATED STRATEGY

In addition to the principles discussed in this chapter, other approaches support the development of a long-term systems approach (Biggs et al., 2012), including the following:

- Establishing monitoring, adaptive management, and learning in the management decision-making process;
- Encouraging experimentation, flexibility, and innovation in management; and
- Broadening participation of multiple community partners in all stages of the planning, implementation, monitoring, and adaptive management processes.

Addressing multiple goals in a systems context amid a changing climate warrants a flexible adaptive management approach (Olsson et al., 2004; Roberts et al., 2016). Especially with the objective of decreasing water use in dust control, innovative experiments are needed at Owens Lake (Roberts et al., 2016), including a focus on hybrid dust management approaches.

Providing advice on the implementation of a long-term, integrated strategy for Owens Lake is beyond the scope of this report but could be a topic in future reports by the Owens Lake Scientific Advisory Panel. As indicated in the 2014 Stipulated Judgment,[2] this report represents the first in an expected series of reports to be prepared by the panel assembled by the National Academies of Sciences, Engineering, and Medicine. Through continued engagement, the panel will provide ongoing assessments and scientific advice on the challenges to developing sustainable approaches to reduce dust in the Owens Valley. Through its upcoming activities, the panel may provide valuable advice on implementing the recommendations in this report, especially regarding the application of landscape-based, systems approaches for assessing dust control configurations at Owens Lake and the use of PM_{10} concentration measurements to quantify emissions from control areas (see Chapter 2).

CONCLUSIONS AND RECOMMENDATION

This section presents the panel's key conclusions and a recommendation concerning a systems approach to address current and future challenges at Owens Lake.

> **Conclusion:** Further improvements in dust control to reduce PM_{10} concentrations with lower water use, while protecting environmental resources, ultimately will result in tradeoff challenges that are not fully understood today. Such tradeoffs will need

[2] Stipulated Judgment in the matter of the City of Los Angeles v. the California Air Resources Board et al. Superior Court of the State of California, County of Sacramento. Case No. 34-2013-80001451-CU-WM-GDS. Approved by the court on December 30, 2014.

to be evaluated in a systematic way to identify the best selection and application of DCMs and to understand how alteration of one DCM can affect overall lake-wide performance.

Conclusion: The complex challenge that Owens Lake PM_{10} management faces in meeting multiple goals, including dust control, protection of environmental and cultural resources, and water savings, can be addressed in an effective manner through a landscape-based, systems approach that is flexible and adaptive. Such an approach also has the potential to decrease energy use and long-term maintenance costs. In addition to managing multiple goals and recognizing tradeoffs, a systems approach at Owens Lake would consider and plan for key factors that affect attainment of the goals both at individual sites and collectively. Such factors include local conditions, spatial and temporal variability, and the potential for self-maintenance, sustainability, and resilience.

Recommendation: To support the development of a landscape-based, systems approach with multiple goals, dust control configurations should be assessed within a lake-wide system, considering long-term management of air quality, surface water and groundwater, and salinity; protection of cultural resources; and the regional significance of habitat types and other ecosystems services in the Owens Valley.

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Appendix A

Panel Member Biosketches

David T. Allen (NAE), Chair, is the Gertz Regents Professor of Chemical Engineering, and the director of the Center for Energy and Environmental Resources, at the University of Texas at Austin. He is the author of 7 books and more than 250 papers, primarily in the areas of urban air quality, the engineering of sustainable systems, and the development of materials for environmental and engineering education. Dr. Allen has been a lead investigator for multiple air quality measurement studies, which have had a substantial impact on the direction of air quality policies. He directs the Air Quality Research Program for the state of Texas, and he is the founding Editor-in-Chief of the American Chemical Society's journal *ACS Sustainable Chemistry & Engineering*. The quality of his work has been recognized by the National Science Foundation, the AT&T Foundation, the American Institute of Chemical Engineers, the Association of Environmental Engineering and Science Professors, and the state of Texas. He has served on a variety of governmental advisory panels and from 2012 to 2015 chaired the U.S. Environmental Protection Agency's Science Advisory Board. Dr. Allen received his B.S. degree in chemical engineering, with distinction, from Cornell University. His M.S. and Ph.D. degrees in chemical engineering were awarded by the California Institute of Technology. He has held visiting faculty appointments at the California Institute of Technology, the University of California, Santa Barbara, and the Department of Energy.

Newsha K. Ajami is the director of Urban Water Policy with Stanford University's Water in the West program. Her work is focused on sustainable water resource management, water policy, innovation, and financing, and the water-energy-food nexus. Her research has been interdisciplinary and impact driven, focusing on the improvement of the science-policy-stakeholder interface by incorporating social and economic measures and effective communication. Dr. Ajami is a two-term gubernatorial appointee to the Bay Area Regional Water Quality Control Board. Before joining Stanford, she worked as a senior scholar at the Pacific Institute and served as a Science and Technology fellow at the California State Senate's Natural Resources and Water Committee, where she worked on various water and energy related legislation. She has published many highly cited peer-reviewed articles, coauthored two books, and contributed opinion pieces to *The New York Times*, *San Jose Mercury*, and the *Sacramento Bee*.

She was the recipient of the 2005 National Science Foundation award for AMS Science and Policy Colloquium and ICSC-World Laboratory Hydrologic Science and Water Resources Fellowship from 2000 to 2003. She serves as member of the National Academies Water Science and Technology Board. Dr. Ajami received a B.S. degree in civil and environmental engineering from Tehran Polytechnic, M.S. degree in hydrology and water resources from the University of Arizona, and Ph.D. degree in civil and environmental engineering from the University of California, Irvine.

Roya Bahreini is an associate professor of atmospheric science at the University of California, Riverside. She specializes in ground-based and laboratory measurements of particulate matter composition and microphysical properties; air quality; and aerosol direct- and indirect-effects on climate. Dr. Bahreini conducts particle monitoring and source characterization at the Salton Sea. She received the National Science Foundation CAREER award in 2015, the Thomson Reuters Highly Cited Researchers award in 2014, and The World's Most Influential Scientific Minds award in 2014. Dr. Bahreini received a bachelor's degree in chemical engineering from the University of Maryland, College Park, and M.S. and Ph.D. degrees in environmental science and engineering from the California Institute of Technology.

Pratim Biswas (NAE) is professor and chair of the Department of Energy, Environmental & Chemical Engineering at Washington University in St. Louis. He also serves as an assistant vice chancellor of international programs. Dr. Biswas' research areas include aerosol science and engineering with applications in energy and environmental nanotechnology, nanoparticle synthesis, advanced material synthesis, solar energy utilization, electronics, air pollution control, sensors, atmospheric issues, and thermal sciences. Dr. Biswas has played a leading role at the national and international arena in the field of aerosol science and technology by serving on several national committees. He was appointed to the National Academy of Engineering in recognition of his advancement in the science of aerosol dynamics and particle removal technologies. He has more than 350 refereed journal publications, has presented several invited presentations nationally and internationally, holds eight patents, and has spun off two start-up companies based on his inventions. Dr. Biswas received a bachelor's degree in technology from the Indian Institute of Technology, M.S. degree from the University of California, Los Angeles, and a Ph.D. degree in mechanical engineering from the California Institute of Technology.

Valerie T. Eviner is a professor in the Department of Plant Sciences at the University of California, Davis (UC Davis). In addition, she is an associate ecologist in the UC Davis Agriculture Experiment Station. Her research interests are in using a mechanistic understanding of plant-soil, plant-plant, plant-microbe, and plant-animal interactions to increase the understanding and effective management of ecosystem services, plant invasions, restoration, plant community composition, biogeochemical cycling, global change, grazing systems, and resilience of ecosystem structure and function. Her current projects include exploring the impacts of resource manipulations on plant competitive interactions. Dr. Eviner is a fellow of the Ecological Society of America and an associate editor of *Restoration Ecology*. She received a B.A. in biology from Rutgers University and a Ph.D. in integrative biology from the University of California at Berkeley.

Gregory S. Okin is a professor in the Department of Geography and the Institute of the Environment and Sustainability at University of California, Los Angeles. His research focuses on the geomorphology, soils, and vegetation of arid and semiarid lands at scales ranging from meters to region, including aeolian geomorphology and the interaction between soils, vegetation, and climate in deserts. He conducts field and laboratory research and employs remote sensing and spatial modeling to understand fine-scale processes, meso-scale patterns, and global-scale Earth system interactions. Dr. Okin is a member of the editorial board of *Ecosphere*, a former editor of the *Reviews of Geophysics*, and an associate editor of *Journal of Geophysical Research—Earth Surface*. He received a B.A. degree in chemistry and philosophy from Middlebury College and an M.S. degree in geology and Ph.D. degree in geochemistry, both from the California Institute of Technology.

Armistead G. Russell is the Howard T. Tellepsen Chair and Regents' Professor of Civil and Environmental Engineering at Georgia Institute of Technology, where his research is aimed at better understanding the dynamics of air pollutants at urban and regional scales and assessing their impacts on health and the environment to develop approaches to design strategies to effectively improve air quality. Dr. Russell was a member of the U.S. Environmental Protection Agency's Clean Air Science Advisory Committee (CASAC) and a member of the National Academies' Board on Environmental Studies and Toxicology, and he has served on multiple National Academies committees. He chaired the CASAC NOx-SOx, Secondary NAAQS review panel, the Ambient Air Monitoring Methods Subcommittee, and the Council on Clean Air Compliance Analysis' Air Quality Modeling Subcommittee, and was on the Health Effects Institute's Report Review Committee. He was an associate editor of the journal *Environmental Science and Technology*. He co-directed the Southeastern Center for Air Pollution and Epidemiology and co-directs the National Science Foundation Sustainability Research Network "Environmentally Sustainable, Healthy and Livable Cities" project. He earned a B.S. degree from Washington State University and M.S. and Ph.D. degrees from the California Institute of Technology, all in mechanical engineering.

Scott Tyler is a hydrologist specializing in hydrology and environmental fluid dynamics at the University of Nevada, Reno. He is a professor with the Department of Geological Sciences and Engineering and adjunct professor in the Department of Civil and Environmental Engineering. Dr. Tyler's areas of focus span the wide range of hydrology and environmental fluid dynamics. His research is focused on water, solutes, and energy fluxes in the subsurface, as well as their exchange into the atmosphere. He serves as the director of the Centers for

Transformative Environmental Sensing Programs, a National Science Foundation–supported instrument center, focusing on the development of distributed fiber optic sensing and wireless sensing of environmental variables. Dr. Tyler received a B.S. degree in mechanical engineering from the University of Connecticut, M.S. degree in hydrology from the New Mexico Institute of Mining and Technology, and Ph.D. degree in hydrology/hydrogeology from the University of Nevada, Reno.

Robert Scott Van Pelt is a soil scientist in Wind Erosion and Water Conservation Research for the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA). His research interests are mainly in soil-atmosphere interactions, including aeolian processes in landscapes, ranging from tilled production fields to native plant communities. In addition to direct measurements of horizontal and vertical sediment transport using passive and optically based sensors, Dr. Van Pelt uses chemical tracers to follow the movement of particles from their source to their vector of transport or place of deposition. He is actively involved in the current USDA-ARS effort to investigate and develop models of rangeland wind erosion. In addition, he is working on a research project to optimize water use efficiency for environmentally sustainable agricultural production systems in semi-arid regions. Dr. Van Pelt received a B.S. in biology and an M.S. in floristics, plant ecology, and climatology from the University of New Mexico; he received a Ph.D. in soil and atmospheric physics from New Mexico State University.

Akula Venkatram is professor of mechanical engineering at the University of California, Riverside. His research is focused on the development and the application of models for the transport and dispersion of air pollutants over urban and regional scales. He was the founding chair of the department of mechanical engineering. Previously, he held positions as the vice president of air sciences at ENSR Consulting and Engineering and the head of model development at the Ontario Ministry of the Environment. Dr. Venkatram has led the development of the first comprehensive long-range acid deposition model—The Acid Deposition and Oxidant Model (ADOM)—which was used in U.S.-Canada negotiations on sulfur and nitrogen emission control. Dr. Venkatram co-edited and contributed to the "Lectures on Air Pollution Modeling" published by the American Meteorological Society. He was member of the team that developed AERMOD, and was a principal contributor to RLINE, the U.S. Environmental Protection Agency (EPA) model for line sources. He is the recipient of the inaugural award from the AMS Committee on Meteorological Aspects of Air Pollution for "contributions to the field of air pollution meteorology through the development of simple models in acid deposition, ozone photochemistry and urban dispersion." His research on modeling the air quality impact of transport-related emissions was recognized in 2010 by EPA, through a Scientific and Technological Achievement Award for "expanding and improving the scientific and regulatory communities' ability to assess the impacts of mobile source emissions." Dr. Venkatram received a B.S. degree in mechanical engineering from the Indian Institute of Technology and a Ph.D. degree in mechanical engineering from Purdue University.

Appendix B

Open-Session Meeting Agendas

OWENS LAKE SCIENTIFIC ADVISORY PANEL

First Meeting

May 3, 2019
Los Angeles Department of Water and Power; 111 North Hope St;
Los Angeles, CA 90012

MEETING AGENDA

Friday, May 3rd

8:30 - 9:50 AM *Panel members and National Academies staff meet in closed session.*

OPEN SESSION

10:00 PDT **Opening Remarks and Introduction of Panel Members**
Dr. David Allen, OLSAP Chair

Owens Lake History and Context

10:05 **Regulatory and Dust Control Implementation History**
Phillip L. Kiddoo, Air Pollution Control Officer, GBUAPCD

10:30	**Owens Lake Dust Mitigation Project Phases** Jaime Valenzuela, Manager of Owens Lake Dust Mitigation Group, LADWP
10:45	**Overview of Dust Control Measure Development History** Dr. Grace Holder, Senior Scientist, GBUAPCD
11:15	**Questions from the Panel**

Current Dust Control Status and Regulatory Requirements

11:30	**Current Dust Control Status, BACM, and Regulatory Requirements** Ann Logan, Deputy Air Pollution Control Officer, GBUAPCD
11:45	**LADWP Current Operations, Maintenance, Infrastructure and Constraints** Jennifer Wong, Manager of Owens Lake Engineering, LADWP
12:00	*Lunch break*

Key Constraints in Considering Alternative Dust Control Measures

1:00	**District's Constraints and Considerations** Phillip L. Kiddoo, Dr. Grace Holder, and Ann Logan, GBUAPCD
1:15	**LADWP Regulatory Constraints, Obligations, and Considerations** Arrash Agahi, Capital Development & Implementation, LADWP
1:35	**Questions from the Panel**

Specific Measures for Panel Consideration

1:55	**Shrubs** Dr. Evan Burgess, Air Sciences, Inc.
2:40	**Shallow Flooding Wetness Cover Refinement Test/Soil Moisture** John Bannister, Air Sciences, Inc.

3:25 **District Recommendations for the Panel**
Dr. Grace Holder, Senior Scientist, GBUAPCD

3:30 *Break*

3:40 **Questions from the Panel**

Perspectives on OLSAP's Task

Allotted times include 5 minutes for questions from the panel.

4:00 Jennifer Mattox, Science Policy Advisor, California State Lands Commission

4:20 Kathy Bancroft, Tribal Historic Preservation Officer, Lone Pine Paiute-Shoshone Reservation

4:40 Danelle Gutierrez, Tribal Historic Preservation Officer, Big Pine Paiute Tribe of Owens Valley

Opportunity for Public Comment

5:00 *To make a comment, sign-up by 4:00 PM (PDT), either at the registration table outside of the meeting room or via email to Carly Brody at CBrody@nas.edu. Each speaker will have a maximum time limit of 3 to 5 minutes. Accompanying written materials are encouraged.*

5:30 **End of Open Session**

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

OWENS LAKE SCIENTIFIC ADVISORY PANEL

Information Gathering via Webinars

July 17-18, 2019

MEETING AGENDA

Wednesday, July 17

OPEN SESSION

6:00 PM (EDT)	**Opening Remarks and Introductions of OLSAP Members** Armistead Russell, panel member
6:10	**Air Quality Modeling for the 2016 SIP Attainment Demonstration** Ken Richmond, RamBoll
6:40	**Questions from the panel**
6:55	**Previous BACM Performance and Modelling Approaches Used for Predicting BACM Impact** Grace Holder, GBUAPCD
7:10	**Questions from the panel**
7:20	**BACM Testing and Assessment** Grace Holder, GBUAPCD
7:35	**Questions from the panel**
7:45	**End of open session**

Thursday, July 18

OPEN SESSION

6:00 PM (EDT)	**Opening Remarks and Introductions of OLSAP Members** David Allen, panel chair
6:10 PM	**Hydrology of Owens Valley and Owens Lake and Effects of the Sustainable Groundwater Management Act (SGMA)** Saeed Jorat, LADWP, Eastern Sierra Environmental Group
6:40	**Questions from the panel**
6:55	**End of open session**

OWENS LAKE SCIENTIFIC ADVISORY PANEL

Information-Gathering Session

July 23, 2019
Los Angeles Department of Water and Power (LADWP) Sulfate Facility
111 Sulfate Rd, Keeler CA, 93530

AGENDA

<u>Tuesday, July 23rd</u>

7:30 – 11:30 AM **Owens Lake Field Orientation (Part 1) (PDT)**

OPEN SESSION AT SULFATE FACILITY

1:00 **Opening Remarks and Introduction of Panel Members**
David Allen, OLSAP Chair

1:10 **CDFW Role in the Owens Dry Lakebed Management**
Patricia (Trisha) Moyer, California Department of Fish and Wildlife

1:25 **Peter Pumphrey and Michael Prather, Eastern Sierra Audubon**

2:10 **Ecology of Owens Lake**
Jeffrey Nordin, LADWP

2:45 *Break*

3:00 **Climate Change Study on Eastern Sierra Watershed**
Theresa Kim, LADWP

Opportunity for Public Comment

3:45 *To make a comment, sign-up by 3:00 PM (PDT) at the registration table in the meeting room. Each speaker will have a maximum time limit of 3 to 5 minutes. Written comments can be submitted remotely to Rita Gaskins via either the Zoom chat function or email at RGaskins@nas.edu.*

4:30 **End of Open Session**

EFFECTIVENESS AND IMPACTS OF DUST CONTROL MEASURES FOR OWENS LAKE

OWENS LAKE SCIENTIFIC ADVISORY PANEL

Information Gathering via Webinar

August 20, 2019

MEETING AGENDA

Tuesday, August 20

OPEN SESSION

10:30 AM (EDT) **Opening Remarks and Introductions of OLSAP Members**
Dave Allen, panel chair

10:35 **Update on Air Quality Modeling and Monitoring in the Owens Valley Planning Area for the PM_{10} National Ambient Air Quality Standards**
Ann Logan, GBUAPCD

10:50 **Questions from the Panel**

11:05 **Potential Dust Control Measures at Owens Lake: Brief Summaries Regarding Performance, Applicability, and Other Aspects**

1. Natural Solid Roughness Elements
2. Engineered Solid Roughness Elements
3. Engineered Porous Roughness Elements
4. Natural Porous Roughness Elements
5. Biological Crusts

Grace Holder, GBUAPCD

11:30

6. Shrubs
7. Moat and Row
8. Sand Fences
9. Solar Panels
10. Soil Binders
11. Soil Moisture
12. Shallow Flood Wetness Cover Refinement

Mark Schaaf, Air Sciences Inc. (consultant to LADWP)

12:05 **Questions from the Panel**

12:30 **End of Open Session**