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Scoping of future research opportunities to reduce impacts of fugitive dust on Reclamation's lands at the Salton Sea and understand impacts of a receding Salton Sea on the Colorado River Basin

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14. ABSTRACT

This literature review focused on two topics related to the Salton Sea (Sea): reducing impacts of fugitive dust on Reclamation's lands at the Sea and understanding the impacts of a receding Sea on Colorado River supplies. The literature review aimed to identify techniques to reduce impacts of fugitive dust emissions from the exposed playa and existing research linking the Sea to precipitation patterns, and where additional research on these topics is needed.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Bureau of Reclamation
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Acronyms and Abbreviations

ASU	Arizona State University
BACM	Best Available Control Measure
BLM	Bureau of Land Management
CDFW	California Department of Fish and Wildlife
CNRA	California Natural Resources Agency
DCM	Dust Control Measure
DOI	Department of Interior
DRI	Desert Research Institute
DWR	California Department of Water Resources
EICP	Enzyme-Induced Carbonate Precipitation
EPA	U.S. Environmental Protection Agency
IID	Imperial Irrigation District
LADWP	Los Angeles Department of Water and Power
NAM	North American Monsoon
NASEM	National Academy of Sciences, Engineering, and Medicine
OLSAP	Owens Lake Scientific Advisory Panel
PHES	Pumped hydroelectric energy storage
QSA	Quantification Settlement Agreement
Reclamation	Bureau of Reclamation
S&T	Science and Technology
SCAO	Bureau of Reclamation's Southern California Area Office
Sea	Salton Sea
SS AQM Program	Salton Sea Air Quality Mitigation Program
USFWS	United States Fish and Wildlife Services
YAO	Yuma Area Office

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Executive Summary

As the Salton Sea (Sea) recedes, more playa is exposed and may become emissive, contributing to significant air quality and public health concerns. The Salton Sea also provides important ecological habitats, particularly for migratory waterfowl and the Pacific Flyway. In addition to public health and ecological concerns, there is some suggestion that reduced evaporation from the Sea could impact precipitation in the lower Colorado River basin.

This report summarizes a literature review aimed at identifying existing research, and where additional research is needed, on two topics at the Salton Sea:

1. Reducing impacts of fugitive dust on Reclamation's lands at the Sea, and
2. Understanding the impacts of a receding Sea on Colorado River supplies.

Additional research could be completed to complement ongoing efforts to mitigate dust emissions at the Salton Sea. Projects are currently ongoing to evaluate surface roughening and managed vegetation, and there is also a pilot study evaluating five chemical dust suppressants. Recent evaluation of dust control measures (DCMs) has also been completed for Owens Lake, a smaller lakebed in California that is facing dust control issues similar to the Salton Sea. This Owens Lake evaluation could be used to complement research on DCMs at the Salton Sea. Potential research opportunities were also identified and discussed in the final report for that study. Two other emerging dust suppression techniques include enzyme-induced carbonate precipitation (EICP) and microbially-induced carbonate precipitation (MICP). These techniques are being considered in small-scale benchtop studies that are one component of a larger chemical dust suppression pilot study at the Sea, and future research could involve field-testing these techniques on exposed playa.

A draft paper, titled Pumped Hydroelectric Energy Storage (PHES) and Rescue of the Salton Sea, was submitted to the Southern California Area Office (SCAO) from a retired engineer associated with the San Diego Water Technology Alliance (draft paper). The draft paper indicates that the approximately 1.3 million acre-feet of annual evaporation from the Sea contributes to rainfall in the Colorado River basin and hypothesizes that reduced evaporation from a receded Sea may impact the entire basin. The draft paper proposes ocean water import projects to restore the Sea to its original shoreline. The water import projects proposed would include a PHES component to make the projects more feasible. One of the projects would involve importing water from the Sea of Cortez through the flooding of Laguna Salada, a dry lakebed in Mexico. Although there many obstacles to overcome for such a project, the draft paper predicts that the flooding of Laguna Salada could have positive impacts on the North American Monsoon (NAM) and on dust suppression at the Sea. It proposes a future atmospheric modeling research study with the Desert Research Institute (DRI) to quantify the impacts such a project may have on the NAM.

1 Introduction

Historically, natural flooding of the Colorado River has caused large seas to cyclically form and dry in the Salton Sea basin. The current Salton Sea, located in southern Riverside and northern Imperial counties, was created in 1905 when the Colorado River flooded, destroyed a major canal under construction, and poured river water into the Salton sink for more than two years. The main recharge water for the Salton Sea today comes from agricultural runoff from the Coachella and Imperial subareas. In addition, the Sea is an extremely critical resource and important food source for more than 400 species of resident, migratory, and special status birds, including several species of special concern. It is an important part of the Pacific Flyway and has become one of the most important wetlands for birds in North America (California Department of Fish and Wildlife, 2020). In the recent past, the Salton Sea also was a popular spot for recreational boating and fishing.

Reclamation's interest in the Salton Sea is related to agricultural drainage from nearby lands irrigated by Colorado River water. The Bureau of Reclamation (Reclamation) owns approximately 90,000 acres of land under and adjacent to the Salton Sea, and the Department of Interior (DOI) owns approximately 126,000 acres. In 2017, mitigation flows to the Sea as required under the Quantification Settlement Agreement (QSA) ended and Sea levels began to decline at a faster rate, exposing more lands that may become emissive over time and contributing to human health concerns in the region, which already has some of the worst air pollution in the country. Imperial County has the highest rate of asthma-related emergency room visits for children in California (James, 2017). The Salton Sea also provide important ecological habitats and is an important part of the Pacific flyway.

This report summarizes a literature review aimed at identifying existing research, and where additional research is needed, on two topics at the Salton Sea:

1. Reducing impacts of fugitive dust on Reclamation's lands at the Sea, and
2. Understanding the impacts of a receding Sea on Colorado River supplies.

1.1 Project Background

According to the Audubon Society, the Salton Sea is "one of the most important places for birds in North America" and "as the Sea changes, we will face losing a vital part of the Pacific Flyway and face a toxic dust bowl that will threaten public health for more than a million Californians" (Audubon California, 2020). Hazard's Toll, a study report from the Pacific Institute, estimated that the cost for no action at the Sea could be as much as $70 billion over the next 30 years, largely from health care and environmental costs as well as decreased property values and tax revenues (Cohen, 2014).

The DOI's Clean Air Act (42 U.S.C. § 7401) responsibilities at the Sea may be significant should conditions worsen. Under the Clean Air Act, Reclamation may be required to provide a comprehensive inventory of actual emissions from all sources and implement a plan for reducing emissions using available control measures within specific and enforceable timeframes. Reclamation estimates that by 2025 approximately 13,200 acres of DOI lands (Reclamation: 5,614 acres, US Fish and Wildlife Service (USFWS): 5,409 acres and Bureau of Land Management (BLM): 2,180 acres) will be exposed from a receding Sea. Using extremely conservative estimates related to air quality mitigation costs at Owens Lake, mitigation for these lands could cost $337 million in the next 10 years.

In addition to addressing public health issues and mitigation costs, recent research suggests that a restored Sea could benefit the lower Colorado River basin through increased precipitation. A draft paper submitted to the Southern California Area Office (SCAO) estimates that the approximately 1.3 million acre-feet of annual evaporation from the Sea contributes to rainfall in the Colorado River basin. A reduction in the surface area and volume of water in the Sea would cause a reduction in evaporation, and therefore may contribute to reduced rainfall in the Colorado River basin, an area that is already facing water reliability issues. The draft paper identifies future research opportunities such as modeling the impacts of reduced evaporation from the Salton Sea on the Colorado River basin.

2 Dust Suppression

One topic this project focused on is dust suppression at the Salton Sea. As more playa at the Sea becomes exposed, there is potential for increased dust emissions. Challenges to dust control and air quality mitigation at the Sea include soil suitability, a lack of water resources, and sand intrusion from upwind desert (Imperial Irrigation District, 2019).

2.1 Techniques currently in use at the Salton Sea

The Imperial Irrigation District (IID) developed the Salton Sea Air Quality Mitigation (SS AQM) Program to address air quality concerns from the QSA water transfer agreement and implement dust control measures on exposed playa at the Salton Sea (Formation Environmental, LLC et al., 2016). The SS AQM Program will also coordinate DCM pilot projects/studies and work with the local air quality districts and the U.S. Environmental Protection Agency (EPA) to expand the list of approved best available control measures (BACMs). Per the SS AQM report, only water efficient vegetation (with at least 50% cover), shallow flooding, chemical dust suppressants, and gravel cover were approved by the Imperial County Air Pollution Control District Rule 804. The SS AQM Program anticipates that the following DCMs will also be approved as BACMs, however:

- Vegetated swales
- Plant community enhancement
- Moat and row
- Water efficient vegetation
- Surface roughening
- Shallow flooding
- Gravel cover
- Alternative land use (e.g. reclamation of agricultural land or energy generation projects)
- Species conservation habitat and other habitat-based uses

The water efficient vegetation DCM is an approved BACM when at least 50% vegetated cover is achieved. The impact of differing levels of infrastructure, vegetation density, and vegetation uniformity on control efficiency could be further evaluated for this DCM, which is why it is also included in the bulleted list above. The plant community enhancement DCM differs from water efficient vegetation in that it expands use of existing plant communities. Each DCM in the bulleted list is discussed in further detail in Appendix E of the SS AQM Program report. Cost estimates from that report are shown in Figure 1 (Formation Environmental, LLC et al., 2016). IID developed these cost estimates from their own program data, suppliers, and the Los Angeles Department of Water and Power (LADWP).

<u>From SS AQM Program Report:</u>

TABLE 3-9 ESTIMATED DUST CONTROL MEASURE UNIT CAPITAL AND O&M COSTS (2014$)

Dust Control Measure	Capital (Per Acre)	Estimated O&M (% of Capital)	Information Source
Surface Roughening	$400	75.00%	IID AQ Program to date
Moat and Row	$14,000	10.00%	LADWP personal communication
Dust Suppressants	$2,000	100.00%	Cargill (Magnesium Chloride)
Vegetation Enhancement	$9,000	7.50%	IID AQ Program to date
Vegetative Swale	$17,000	7.50%	IID AQ Program to date
Managed Vegetation	$25,000	4.50%	LADWP personal communication
Shallow Flood	$25,000	2.00%	LADWP personal communication
Brine Stabilization	$21,000	0.25%	LADWP personal communication
Gravel Cover (2 inch thickness)	$36,000	0.25%	LADWP personal communication
Gravel Cover (4 inch thickness)	$48,000	0.25%	LADWP personal communication

Figure 1. Cost estimates for DCMs at the Salton Sea from the SS AQM Program, July 2016 (Formation Environmental, LLC et al., 2016).

As part of the SS AQM Program, pilot studies for DCMs such as surface roughening and vegetation enhancement have been completed and are currently ongoing at the Sea. The latest Proactive Dust Control Plan recommended several projects that include surface roughening followed by a combination of surface roughening and vegetation establishment. While surface roughening is effective, waterless, and can be quickly implemented, it is not suitable for sites with predominantly coarse-grained sandy soils since the ridges rapidly degrade (Formation Environmental, LLC et al., 2020). Another pilot study on surface stabilizers (chemical dust suppressants) is also ongoing and is expected to be complete in winter 2020 (Formation Environmental, LLC, 2019). Chemical dust suppressants are further discussed in section 2.3.1.

Investigations into surface water and groundwater resources for use with DCMs was also recommended for the SS AQM program, particularly in areas that are not suitable for surface roughening. Groundwater in particular may be able to help establish vegetation. One such groundwater investigation project includes a test well in the Tule Wash Planning Area to obtain water quantity and quality data (Formation Environmental, LLC et al., 2020).

A draft Dust Suppression Action Plan (DSAP) was also recently developed through the Salton Sea Management Program, led by the California Natural Resources Agency (CNRA), the California Department of Water Resources (DWR), and the California Department of Fish and Wildlife

(CDFW). The Dust Suppression Action Plan will use data collected and analyzed by the IID and will expedite dust control projects through streamlined planning and permitting processes. It divides projects into Phase A and Phase B. Surface roughening will be used for dust control with Phase A projects. DCMs anticipated for Phase B projects include vegetation, surface roughening, gravel cover, physical barriers, and ponding water. The Dust Suppression Action Plan also notes lack of water supply sources as a challenge but indicates that groundwater and other sources are being evaluated (Salton Sea Management program, 2020).

2.2 Techniques evaluated for Owens Lake

Owens Lake is smaller and in a cooler, less arid climate than the Salton Sea. The Salton Sea is approximately 343 square miles (The Salton Sea Authority, 2017) and temperatures typically vary from 43 degrees Fahrenheit (°F) in the winter to 107°F in the summer (Weather Spark, 2020). Owens Lake was approximately 100 square miles prior to the 20th century but has a treated area of 27 square miles (U.S. Geological Survey, 2017), and the average temperatures typically vary from 24°F in the winter to 97°F in the summer (Weather Spark, 2020). Like the Salton Sea, the mineral composition of Owens Lakes soils is dominated by sodium carbonate and sodium sulfate, causing more easily erodible salt crusts (NASEM, 2020).

As of May 2019, the LADWP had spent about $2.1 billion for dust control at Owens Lake and uses an average of approximately 60,000 AF/yr of freshwater for DCMs (NASEM, 2020). DCMs at Owens Lake include shallow flooding (most used by surface area), managed vegetation, and gravel cover. Shallow flooding is currently the most common DCM in use at Owens Lake, although other DCMs are being evaluated to reduce reliance on freshwater supplies.

In response to the 2014 Stipulated Judgement, the LADWP and Great Basin Unified Air Pollution Control District contracted with the National Academy of Science, Engineering, and Medicine (NASEM) to establish the Owens Lake Scientific Advisory Panel (OLSAP). The OLSAP evaluated DCMs at Owens Lake and prepared a report detailing their effectiveness and impact (NASEM, 2020).

Information gathered from the OLSAP's evaluation could be used in evaluating DCMs for the Salton Sea. The primary focus of the OLSAP evaluation on DCMs was reducing dust emissions while reducing water use. Associated energy, environmental impacts, and durability/reliability of the DCMs were also considered. At the Salton Sea, however, creating aquatic habitat may be of equal importance to dust suppression, but require more water use.

In total, 15 DCMs were evaluated, six of which are considered approved BACMs. A summary of these DCMs is provided in Table 1 (BACMs) and Table 2 (non-BACMs). The OLSAP provides a more detailed summary of their findings, which includes reported control efficiency, water use, estimated costs per square mile, environmental, time to full performance, and site suitability as Table 4-1 in their report, Effectiveness and Impacts of Dust Control Measures for Owens Lake (NASEM, 2020). Of the DCMs evaluated, the OLSAP identified precision surface wetting, managed vegetation with shrubs, natural porous roughness, and cobbles as the most promising to reduce water use while providing some environmental benefits.

Table 1. Summary of DCMs evaluated by the OLSAP for use at Owens Lake that are considered BACMs (NASEM, 2020)

DCM	Capital Cost	Description based on NASEM Report
Shallow flooding	\$26 – 32 million/mi^2	Has good performance and is reliable but only when there is long-term availability of water supplies. If available, groundwater supplies could be used for shallow flooding, but the impact of local groundwater pumping would need to be considered. It provides environmental benefits by creating avian habitat however the water use is significant. It is not yet known how shallow flooding might change soil and groundwater salinity.
Dynamic management with shallow flooding	\$26 – 32 million/mi^2	Involves an operational modification to shallow flooding, in which reflooding only occurs when specific monitoring criteria are met. This allows for a reduction in water use with shallow flooding but requires more monitoring and may decrease the environmental benefits.
Brine with shallow flooding as backup	\$24 million/mi^2	Uses brine or salt crust to cover the soil surface. Shallow flooding is available if the crust deteriorates and has potential to become emissive. The brine crust alone has been shown to be effective, but shallow flooding is currently required for it to be considered a best available control measure (BACM) at Owens Lake until more data is collected. It achieves full performance quickly and works for both sandy and clay soils, although it may not be appropriate upgradient of saline sensitive areas such as managed vegetation. Additional research could help understand the long-term impacts and stability, and possibly allow application without the required shallow flooding backup.
Tillage with shallow flooding as backup	\$0.5 million/mi^2	Tillage is typically very cost effective. Once implemented, a site is monitored and if measurements show insufficient dust control the site is flooded and re-tilled. This is more effective at sites with high-clay content soils (above 50 percent). Sites with sandy soils likely require re-tilling more frequently, sometimes more than once per year depending on weather conditions.
Managed vegetation	\$20 – 36 million/mi^2	Covers and protects the soil surface from wind erosion. It can be effective while also providing environmental benefits, however it takes a longer period of time to establish (often about 3 years) and requires long-term management of groundwater levels and salinity. Management, costs, and suitability depend on site specific conditions such as soil type, salinity, groundwater depth, irrigation water availability and quality, and dust control at adjacent sites. Water use is typically required, especially during the establishment phase, however the amount is dependent on site specific conditions and the types of vegetation selected.

DCM	Capital Cost	Description based on NASEM Report
Gravel cover	\$37 million/mi^2	Does not require water use and has relatively little maintenance. It is typically very effective, although the effectiveness may be reduced when used downwind of other emissive sites. It provides little environmental benefit and requires use of heavy machinery with installation.

Table 2. Summary of DCMs evaluated by the OLSAP for use at Owen's Lake that are not currently considered BACMs (NASEM, 2020)

DCM	Capital Cost	Description based on NASEM Report
Precision surface wetting	No cost data, estimated at approx. \$32 million/mi^2	Uses sprinklers or perforated whip lines in circular areas to create cohesive surfaces and increase humidity over and downwind of the wetted circle. This provides for dust control not only within the wetted circle but also for areas in-between wetted circles. Although it uses less water than shallow flooding, it still requires use of water and requires water distribution infrastructure. Additional research is needed.
Artificial Roughness (4 types) • Solid natural • Solid engineered • Porous natural • Porous engineered	• \$9 – 52 million/mi^2 • \$45 million/mi^2 • No cost estimate • \$64 million/mi^2	These elements change the airstream and reduce the wind's ability to move surface sediments and emit dust. The four types include: • solid natural (e.g. straw bales), • porous natural (e.g. brush piles or "vertical mulch"), • solid engineered, and • porous engineered. Solid natural elements (straw bales) have been used in the Owens Lake area at Keeler Dunes for dust control with up to 92% control efficiency at the center of the array, although issues were observed by the OLSAP during a site visit. Solid engineered roughness and porous engineered roughness have been tested on a small-scale, however porous natural roughness elements have not been tested. These DCMs do not require water use.
Shrubs: Modification of managed vegetation coverage requirements	No cost estimate	Similar to the managed vegetation BACM, although it uses shrubs (i.e. taller plants) with lower percent vegetation cover and less water use. It has a longer establishment time than other DCMs. Watering is required during the establishment and growth phases. Additional research is needed to establish control efficiencies.
Cobbles	No cost estimate	Similar to gravel cover, but the cobbles are larger and less uniform than gravel. Performance is similar to the gravel cover, although cobbles may provide additional environmental benefit since the non-uniform spacing allows for vegetation growth and shelter for non-aquatic species. As with gravel cover, water use is not required. Cobbles are currently used at Owens Lake as part of the Land Art Project.

DCM	Capital Cost	Description based on NASEM Report
Sand Fences	$15 million/mi^2	Modifies airflow and traps mobile sand. Although they don't meet BACM-level control efficiencies for Owens Lake, they are installed in some areas there and are effective for localized reduction of dust levels. They are easy to install and don't require water use.
Solar Panels	$80 – 100 million/mi^2	Could be used to take advantage of the open space and produce energy while potentially providing dust control by reducing ground-level wind speeds. This was tested at Owens Lake, however the solar panels were placed on top of gravel. More investigation is needed to determine control efficiencies of solar panels, particularly if they are not placed on gravel.

Table 3. Summary of DCMs not evaluated for use at Owen's Lake by the OLSAP (NASEM, 2020)

DCM	Capital Cost	Description based on NASEM Report
Chemical stabilizers/soil binders*	No cost estimate	Chemical application that adds a protective layer to the soil surface. Does not require water after application but there are concerns that they are not resilient. Large emissions could occur if the thin layer on the soil surface is compromised. More testing is needed. A flood event interrupted a small-scale field test on soil binders in 2013, and a planned large-scale study to test eight different chemical stabilizers is awaiting regulatory approval.
Biocrusts*	No cost estimate	Provides a protective "living" layer at the soil surface. May be suitable for areas that remain relatively undisturbed over time and have little sand movement. While they can provide ecosystem benefits as well as dust control, they are sensitive to disturbances such as vehicle and foot traffic. Once disturbed, they are slow to recover and vulnerable to wind erosion.

*These DCMs were not evaluated in detail for use at Owens Lake since the panel felt that near-term applicability was limited due to either regulatory agencies or available science.

2.3 Other dust suppression techniques

As indicated in Table 1, chemical stabilizers/soil binders and biocrusts were not evaluated in detail by the OLSAP for use at Owens Lake. There is an ongoing pilot study for soil binders at the Salton Sea, however. These DCMs are discussed further in section 2.3.1. Two emerging bio-inspired techniques may also provide dust control benefits. These techniques, Enzyme-Induced Carbonate Precipitation (EICP) and Microbially-Induced Carbonate Precipitation (MICP), are discussed in section 2.3.2 and section 2.3.3, respectively. Chemical stabilizers/soil binders and the bio-inspired techniques, if successful, may offer lower cost DCM options. Per Figure 1 in section 2.1, dust suppressants were estimated to be about $2,000/acre, which was less than all the other DCMs except for surface roughening (Formation Environmental, LLC et al., 2016).

2.3.1 Chemical Dust Suppressants

Chemical dust suppressants are commonly used for dust control on unpaved roads and at construction sites, airbases, helipads, or other disturbed lands (Jones et al., 2013; USACE, 2006). While there are over 150 different proprietary blends for dust suppression, these generally fall into seven categories: water absorbing, organic non-petroleum or natural polymers, organic petroleum and petroleum resins, synthetic polymer emulsions, synthetic fluids, electrochemical/sulfonated oils, and enzymes (Jones et al., 2013). Site specific conditions and soil properties may impact performance for each type. A summary of these seven categories of chemical dust suppressants is provided in Table 2.

Table 4. Summary of chemical dust suppressants

Category	Examples	Details
Water absorbing	Magnesium chloride and calcium chloride	These work by absorbing small amounts of water from the air. They require minimum humidity levels and do not work well in arid environments (Jones et al., 2013; USACE, 2006).
Organic non-petroleum or natural polymers	Lignosulfonates, tree resins, tree oils, vegetable oils and molasses-based products	Use by-products from plant-based industries (e.g. pulpwood processing) and act as "glue" to hold soils together (Jones et al., 2013).
Organic petroleum and petroleum resins	Diluted asphalt emulsions	These work by binding surface soils through cementing action (Jones et al., 2013). Most have been eliminated from use, with exception of asphalt emulsions, due to environmental impacts (USACE, 2006).
Synthetic polymer emulsions	Vinyl acetate or acrylic-based copolymers suspended in an aqueous phase by surfactants	They are typically 40 – 50% solids. After application, they bind soils together as the aqueous medium evaporates (Jones et al., 2013; USACE, 2006).
Synthetic fluids	Synthetic base fluids and unique formulations of synthetic iso-alkanes	Forms a reworkable binder with soils and does not dry or cure over time (Jones et al., 2013; USACE, 2006).
Electrochemical/ sulfonated oils	Surfactants, proprietary products	Uses ionic exchange reactions to reduce plasticity and form an oily protective layer (Jones et al., 2013).
Enzymes	These are usually proprietary products	A central theme of these products involves microbial activity to neutralize clay activity (Jones et al., 2013).

A pilot study at the Salton Sea, developed for the IID as part of the SS AQM Program, is currently testing five dust suppression products. Of the 15 products reviewed, these five were determined to be the most feasible for the study. Most of these products are synthetic polymer emulsions, although the last one (Terra-Ferr) is a blend of lignin liquor (natural polymer), whey, and magnesium chloride (water soluble salt) (Formation Environmental, LLC, 2019). The products are:

- Soiltec®,
- DirtGlue®,
- Dust Control Plus,
- Soil Stabilization Plus, and
- Terra-Ferr.

The pilot study includes benchtop and field tests. The benchtop studies will evaluate the 5 products already described, and will also evaluate two types of bio-inspired techniques: EICP and MICP, which are further discussed in section 2.3.2 and section 2.3.3, respectively. The benchtop studies with bio-inspired techniques will be smaller scale than the benchtop studies with the other 5 dust suppression products being tested (Formation Environmental, LLC, 2019).

2.3.2 Enzyme-Induced Carbonate Precipitation (EICP)

EICP is an emerging dust control technology studied by Arizona State University (ASU) and Reclamation. It accelerates the biocementation process through application of free urease enzyme, which causes a geochemical reaction (hydrolysis of urea) and forms an erosion resistant crust.

From October 2017 to October 2019 Reclamation's Yuma Area Office (YAO) and ASU conducted laboratory tests on EICP. This project, Science and Technology (S&T) 1840, was funded by Reclamation's S&T program. Tests were conducted with soil samples from sites in Yuma, Arizona to evaluate the feasibility of EICP for both mass stabilization and surficial stabilization. The mass stabilization tests showed calcium carbonate precipitation but no cementation of the soils. Future tests were recommended since studies with other soils had shown EICP successful for mass stabilization. The surficial stabilization tests showed that EICP-treated soils have the same strength as water wetted soils. In addition, stabilization from EICP is expected to last longer and require less frequent re-application than wetted soils. The study recommended that surface stabilization tests be completed for soils from highly emissive areas, such as the Salton Sea playa (Gutierrez et al., 2019).

Another study completed a life cycle sustainability assessment for EICP compared to water application for dust control. Although the study indicated that the results were specific to the project site in Maricopa County, it concluded that EICP is potentially more sustainable than water application, and that it could become more viable for fugitive dust control with further development focused on preventing process emissions and reducing production costs (Raymond et al., 2019).

Some challenges to EICP include environmental impact, uniform treatment, costs, and minerology of the precipitates. The potential environmental concern comes from the ammonium by-product. More research is needed on this by-product to determine if it actually is a concern. The other challenge may be uniform treatment, although some research has been done suggesting methods to influence this (Khodadadi et al., 2017). As for costs, the most expensive component is the enzyme, but there maybe be multiple methods for obtaining it. ASU testing at the Center for Bio-Mediated and Bio-Inspired Geotechnics has shown that it can be extracted from plant waste, such as trimmings, and it is typically extracted from the jack bean plant. Other tests have been completed showing it can also be extracted from watermelon seeds, cotton, and desert vegetation. Minerology of the precipitates may be another challenge, however recent testing has shown methods for improvement (Khodadadi et al., 2017).

2.3.3 Microbially-Induced Carbonate Precipitation (MICP)

MICP is another dust control technology that modifies soil properties such as strength, stiffness, and hydraulic conductivity (Wang et al., 2017). Like EICP, it accelerates the biocementation process to create an erosion resistant crust. Unlike EICP, MICP relies on microbial urease to cause the geochemical reaction that forms the crust. It also tends to be a slower process than EICP. While EICP can be instantaneous depending on the mix, MICP can sometimes take months depending on treatment type. Studies have shown that MICP has potential to be effective for dust control, but indicate that soil type and environmental conditions of a site may play a significant role (Meyer et al., 2011).

Challenges for MICP are similar to those of EICP, and more research is needed to better understand the concerns and potential mitigation. Another challenge with MICP is cost, as significant process optimization would be required to reduce costs so that it is competitive with conventional techniques (Khodadadi et al., 2017). Complexity of natural soils may also pose a challenge with MICP, and presence of fine-grained soil particles (i.e. clay and silt), particle size distribution, and mineralogical composition might impact the optimal treatment strategy (Khodadadi et al., 2017).

2.4 Dust Suppression Literature Review Conclusions and Future Research

The primary DCMs being implemented at the Salton Sea include surface roughening and managed vegetation. Owens Lake, a mostly dry lake in California, primarily uses shallow flooding and managed vegetation. These options may not be appropriate for all sites, however. Surface roughening may be less efficient on sites with sandy soils, for example, and managed vegetation requires water use in growth and establishment phases. Shallow flooding requires more significant water use.

The OLSAP evaluated potential DCMs for Owens Lake that could reduce water use compared to shallow flooding. Their evaluation identified and evaluated 15 DCMs, 9 of which are not currently BACMs at Owens Lake. Of these DCMs, the OLSAP identified precision surface wetting, managed vegetation with shrubs, natural porous roughness, and cobbles as the most promising to reduce water use while providing some environmental benefits.

Future research for some of the DCMs evaluated was also identified by the OLSAP. For example, brine and salt crusts is listed as a BACM but only when shallow flooding is provided as a back-up. Future research on the brine crusts would be needed to better understand long-term performance under both wet and dry conditions as well as susceptibility to thermal and geochemical changes before it could be approved without shallow flooding as backup (NASEM, 2020). Research on managed vegetation was also suggested to determine the minimum percent coverage needed, and to investigate mixtures of species with potential to reduce irrigation requirements. Vegetation field studies that may be able to provide this research are currently ongoing at the Salton Sea (Formation Environmental, LLC et al., 2020). The OLSAP also recommended research on control efficiencies associated with precision surface wetting, cobbles, and natural and artificial porous roughness, which were identified as promising DCMs. The potential for hybrid DCMs that combine two or more DCMs for further water reductions and increased benefits was also discussed. The example provided by the OLSAP was precision surface wetting combined with vegetation (NASEM, 2020), but other combinations would likely be possible. For example, current studies at the Salton Sea are being completed using a combination of surface roughening and vegetation enhancement (Formation Environmental et al., 2020).

Five chemical dust suppressants are currently being tested in a pilot study through the SS AQM. In this study, two emerging technologies, EICP and MICP, are also being tested through small-scale benchtop testing. These techniques speed up the biocementation process, creating an erosion resistant crust. EICP, developed at ASU, has been studied previously through Reclamation project S&T 1840. After conducing laboratory studies with soil samples in Yuma, Arizona, Reclamation S&T 1840 concluded that future surface stabilization tests should be done with EICP in areas with highly emissive soils, and suggested Salton Sea playa. Other research has suggested that MICP can be used similarly to EICP and may provide similar benefits. Field testing on Salton Sea playa could help better understand durability of the carbonate crusts formed by EICP and MICP and the fate of the potential ammonia by-products. Field testing these technologies on Salton Sea playa could help determine effectiveness under conditions typical of the Sea such as agricultural runoff.

3 Impact on Colorado River Supplies

Some research may suggest that a restored Salton Sea could benefit the Lower Colorado river basin through increased precipitation. A draft paper submitted to the Southern California Area Office (SCAO) from a retired engineer associated with the San Diego Water Technology Alliance (draft paper) estimates that the approximately 1.3 million acre-feet of annual evaporation from the Sea contributes to rainfall in the Colorado River basin. A reduction in the surface area and volume of water in the Sea would cause a reduction in evaporation, potentially leading to reduced rainfall in the Colorado River basin, an area that is already facing water reliability issues. The draft paper also discusses potential water import projects to the Sea that would incorporate pumped hydroelectric energy storage (PHES). The paper focused on water imports from the Sea of Cortez to the Salton Sea, but indicated that import from the Pacific Ocean may also be possible and feasible if PHES is incorporated.

3.1 Salton Sea and the North American Monsoon

The Salton Sea contains approximately 7.5 million acre-feet of water, is about 35 miles long and 15 miles wide, is 51 feet deep at its deepest point, and has a surface area of approximately 343 square miles. The evaporation rate from the Sea is estimated at approximately 1.3 million acre-feet per year, although this is dependent on weather conditions (The Salton Sea Authority, 2017). Although the Sea is shrinking, the State's Phase I: 10-year Plan outlines restoration projects to protect/improve air quality, wildlife habitat, and water quality while achieving a smaller and more sustainable Sea (Salton Sea Management Program, 2018). If no mitigation or restoration projects are implemented, however, it is estimated that the Sea will shrink to approximately one-third of its current size (The Salton Sea Authority, 2017). Hazard's Toll estimates that over the next fifteen years the Sea's surface will drop by 20 feet and its volume will decrease by more than 60%, by 2030 the surface area will shrink by about 100 square miles, and by 2045 it will shrink by about 150 square miles (Cohen, 2014). As the

Colorado River basin is already facing drought and other challenges, understanding the impacts of a receding Sea on precipitation in the basin is important for water resource management.

A previous study focused on irrigation in California's Central Valley concluded that irrigation strengthened the southwestern water cycle and had a positive impact on precipitation by enhancing summer monsoon rainfall (Lo & Famiglietti, 2013). This study shows potential for changes in surface moisture and evaporation to impact precipitation patterns. In the Central Valley study, it was recommended that further research be conducted to obtain a better understanding of this impact. The study indicated that this impact was particularly important due to uncertainties in groundwater and surface water (primarily from the Colorado River) supply sustainability (Lo & Famiglietti, 2013).

Another study used satellite observations and atmospheric trajectory modeling to evaluate the impacts of ecoregions on their own rainfall. This study analyzed ten water-limited ecoregions, defined as "geographical areas of similar climate and vegetation conditions" (Miralles, et al., 2016). Each of these regions typically had a three-month "growing season" in which precipitation was more likely to occur. The study concluded that vegetation contributed to a baseline supply of precipitation through transpiration and showed the importance of local evaporation contributing to precipitation during dry periods (Miralles et al., 2016).

The Desert Research Institute (DRI) has been studying the North American Monsoon (NAM) to obtain a better understanding of its life cycle and improve regional and global scale modeling. The NAM is critical to the southwestern U.S. and provides a significant amount of the rainfall in northwestern Mexico (60 – 80%), Arizona (35%), and New Mexico (45%) (Desert Research Institute, 2020). Previous studies from the DRI show a correlation between higher sea surface temperatures in the Sea of Cortez and increased rainfall from the NAM, and contributed to other findings that the Sea of Cortez is the primary moisture source for the NAM (Mitchell et al., 2002). Reduced precipitation from the NAM monsoon could have significant consequences on the Colorado River basin, which is already in a 20-year drought. Other studies have indicated that a reduction in summer precipitation (up to 40%) from the NAM is likely to occur with climate change in the southwestern U.S. (Pascale et al., 2017). This highlights the importance of understanding other potential impacts to precipitation in the Colorado River basin.

The draft paper that was submitted to the SCAO suggested modeling studies to determine how Colorado River supplies would be impacted by a reduced Salton Sea, since a smaller Sea would have less evaporation. The proposed research would use advanced climate models to predict potential changes in the Colorado River basin precipitation patterns as they relate to changes at the Salton Sea. The model could compare historical conditions, current conditions, and projected future conditions at the Sea. Differing Salton Sea restoration scenarios could also be evaluated. As discussed further in section 3.2, Salton Sea restoration scenarios proposed by the draft paper include water imports from the Sea of Cortez or the Pacific Ocean and use of pumped hydroelectric energy storage (PHES). Importing water from the Sea of Cortez to the Salton Sea would likely involve flooding of Laguna Salada in Mexico, which would serve as an upper storage reservoir. The draft paper hypothesizes that flooding Laguna Salada could also have positive impacts on the NAM, thereby increasing precipitation in the lower Colorado River basin. The Desert Research Institute (DRI) has been contacted by the Water Tech Alliance in reference to this question and has expressed interest in such a study, in which regional atmospheric modeling would be used to determine whether the possibility exists.

3.2 Salton Sea and Water Imports

The draft paper submitted to the SCAO proposes a PHES-based solution to restore a receded Salton Sea. PHES systems involve two reservoirs (upper and lower) and rely on a high exchange of water. With PHES, energy is generated when stored water is released from the upper to the lower reservoir, and in times of excess energy (low demand) it is pumped back to the upper reservoir. When applying this concept to water import at the Sea, the Salton Sea would serve as the lower reservoir, and either the Pacific Ocean or Sea of Cortez would serve as the upper reservoir. The proposed options involving water import from the Sea of Cortez would utilize and flood Laguna Salada, a dry lakebed in Mexico. Laguna Salada is located in the Sonoran Desert of Baja California in Mexico and is approximately 19 miles southwest of Mexicali. The draft paper states that the use of PHES at the Sea without imported water could also be possible, however it argues that the largest benefits would be seen with the water import projects. A significant amount of research and other studies on environmental impacts would need to be completed for proposed water import projects, particularly for a project that would involve the flooding of Laguna Salada in Mexico (with water import from the Sea of Cortez). These projects would also require preliminary engineering and cost studies to determine if they are feasible. In the case of water import from the Sea of Cortez, binational participation, and benefits to both the U.S. and Mexico, would be necessary.

While importing water from Sea of Cortez would likely be more complex, it is often seen as more economical than imports from the Pacific Ocean. The draft paper states that incorporation of PHES will make these import options more economical, although the option to import water from the Pacific Ocean would likely require a string of intermediate reservoirs and PHES stations. Due to the scale of these projects, it states that it is unlikely that import of water to Salton Sea could actually begin before 2030. Restoration efforts and DCMs would therefore be needed even if a water import project were to move forward. The draft paper indicates that the water import projects could be a follow-on effort to the State's Phase I: 10-year plan.

As mentioned in section 3.1, the draft paper hypothesized that flooding of Laguna Salada could have potentially positive impacts on the NAM. Modeling studies could be completed to predict these impacts. A regional atmospheric modeling study would also help to better understand potential impacts on the Colorado River basin from an ocean water import project.

3.3 Impact on Colorado River Supplies Literature Review Results

In addition to air quality and habit impacts from a receding Salton Sea, impacts to Colorado River basin supplies are also important to understand. Previous studies have suggested that evaporation contributes to the baseline amount of precipitation within a region (Lo & Famiglietti, 2013; Miralles et al., 2016). Currently, approximately 1.3 million acre-feet per year is evaporated from the Salton Sea. An analysis could be completed to see how the evaporation rate changes with a receding Sea, and if this change would have any impact on precipitation within the basin. In addition, water import projects have previously been proposed to restore the Salton Sea, although significant obstacles would need to be overcome. A draft paper submitted to the SCAO proposes to use PHES to make these projects more economical. A regional atmospheric modeling study could help better understand the impacts that these projects would have on precipitation within the Colorado River basin and to the NAM. A regional atmospheric modeling study would also help predict potential changes in the Colorado River basin precipitation patterns as they relate to changes at the Salton Sea. Water Tech Alliance and the Desert Research Institute have expressed interest in such a study.

4 Conclusions

Fugitive dust emissions from Reclamation lands are anticipated to increase as the Salton Sea recedes. It is estimated that by 2025 approximately 13,200 acres of DOI lands (Reclamation: 5,614 acres, USFWS: 5,409 acres and BLM: 2,180 acres) will be exposed. As the land is exposed it is anticipated to become emissive and contribute to negative public health impacts in the region, which already has some of the worst air pollution in the country.

This literature review identified DCMs in use at the Salton Sea, DCMs evaluated for Owens Lake, as well as a few other DCMs. Future research opportunities were suggested by the OLSAP in the 2020 NASEM report. In addition, future research on EICP at the Salton Sea has been suggested by a previous Reclamation S&T project. Due to the complexity of issues at the Salton Sea, the various landowners and jurisdictions, and the many stakeholders required to implement projects and solutions, stakeholder outreach is a critical component for field testing new dust suppression strategies on exposed playa. Through this project's scoping effort, a S&T proposal was submitted seeking funds to work with Salton Sea stakeholders, prioritize dust suppression strategies to be field tested at the Sea, and develop an approach and methodology sensitive to the complex biological, political, and social issues. Another proposal outside this scoping effort had also been submitted to field test EICP and MICP on exposed playa once stakeholder outreach is completed.

No literature was available for review that directly evaluated impacts of a receded Salton Sea on precipitation in the Colorado River basin. Previous studies do suggest that evaporation contributes to baseline precipitation amounts within a basin, however. In addition, water import projects have previously been proposed, but would require significant study and evaluation to overcome obstacles such as costs, feasibility, environmental impacts, and in the event of water import from the Sea of Cortez, binational support. A draft paper submitted to the SCAO suggests a restored Salton Sea would contribute to precipitation in the Colorado River basin. It also predicts that if Laguna Salada, a dry lakebed in Mexico, were flooded as part of a Sea of Cortez water import project, then it could benefit the NAM and thereby increase precipitation to the lower Colorado River basin. The DRI and Water Tech Alliance have previously expressed interest in a regional atmospheric modeling study to test these predictions.

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