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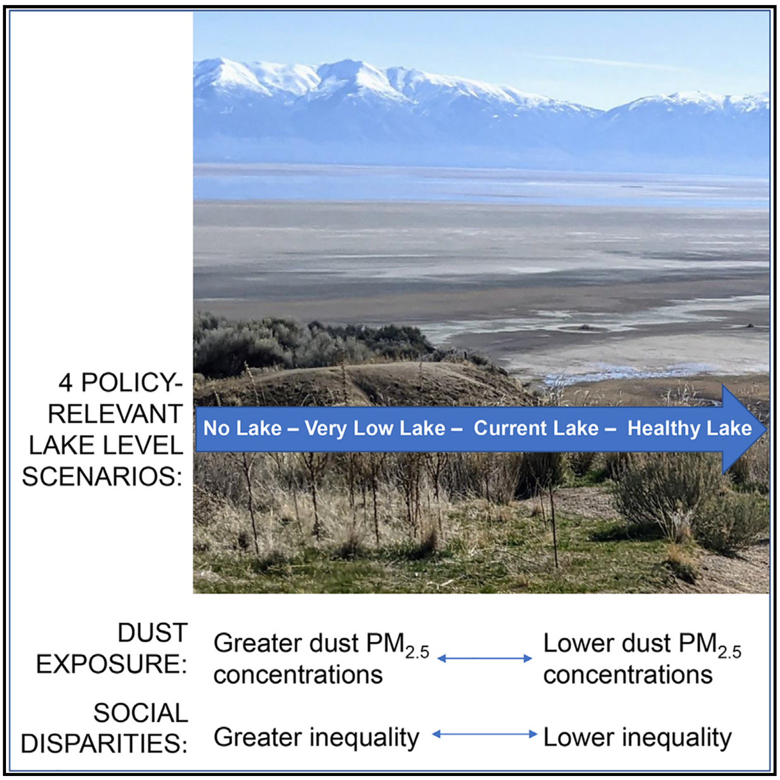
Harmful dust from drying lakes: Preserving Great Salt Lake (USA) water levels decreases ambient dust and racial disparities in population exposure

Graphical abstract



Highlights

- All local residents face potentially unhealthy levels of dust exposure
- Estimates reveal clear exposure disparities based on race/ethnicity
- A healthy lake may attenuate exposure disparities for minoritized groups
- Drying terminal lakes demand policy actions to protect ecological and human health

Authors

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In brief

Lake desiccation is a major ecological catastrophe of the twenty-first century. As lake beds dry, they become sources of fine dust that harms human health. Looking at the case of the Great Salt Lake in Utah, we found that two major benefits of stabilizing healthy water levels for this terminal lake would be to decrease ambient dust and reduce racial disparities in population exposures.

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Harmful dust from drying lakes: Preserving Great Salt Lake (USA) water levels decreases ambient dust and racial disparities in population exposure

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SCIENCE FOR SOCIETY The drying of lakes with no outlets, also called terminal lakes or inland seas, is a major ecological catastrophe of the twenty-first century. As lake beds dry, they become sources of fine dust that harms human health. These lake beds are drying, in part due to decreased inflows of water associated with climate change, but mostly due to increasing human demands for water. We look at the case of the Great Salt Lake in Utah, which has risen to national prominence due to concerns about the loss of habitat, threats to the ski industry due to effects on snow conditions, and the dust plumes. We found that two major benefits of stabilizing water levels for this lake would be to decrease airborne dust and reduce racial disparities in population exposures to dust. This would mitigate the health burden of dust storms for populations living nearby. In this context, halting the lake from drying up would protect ecological and human health while promoting environmental justice.

SUMMARY

Lake desiccation is a global problem associated with increased human water use and climate change. Like other drying lakes, Utah's Great Salt Lake (GSL) is producing health-harming dust. We estimate social disparities in dust fine particulate matter ($PM_{2.5}$) exposures based on four policy-relevant water-level scenarios. Dust $PM_{2.5}$ exposures would increase as GSL levels drop (e.g., from 24.0 $\mu g\ m^{-3}$ to 32.0 $\mu g\ m^{-3}$). People of color and those with no high school diploma would experience disproportionately higher exposures (e.g., 28.4 $\mu g\ m^{-3}$ for Pacific Islanders vs. 26.0 $\mu g\ m^{-3}$ for Whites under very low lake levels). Racial/ethnic disparities would be reduced if GSL water levels rose. If the GSL vanished, racial/ethnic disparities between the highest and lowest exposed groups would be moderate (16.3%). If the GSL stabilized at healthy levels, those disparities would be smaller (7.9%). While all nearby residents face unhealthy dust exposures, findings reveal exposure disparities for socially disadvantaged groups.

INTRODUCTION

Terminal lakes around the world face numerous stressors from human water use and climate change. In many cases, this leads to desiccation with major implications for biodiversity and the health and livelihoods of nearby communities.[1] Terminal lakes (also called inland seas or saline lakes) are fed by rivers but have no outlets. Salt and mineral content concentrates in such lakes' waters due to evaporation, which contributes to their salinity. Saline lakes are of major importance; they represent 44% of the volume and 23% of the area of all lakes on Earth.[2] Water from saline lakes has important uses for agricultural, industrial, and municipal activities; for human recreation; and for local ecosystems, as bird species feed on invertebrates that thrive in briny waters.[2] Major drying terminal lakes are located throughout the world and they include the Great Salt Lake (GSL) (USA), the Aral Sea (Kazakhstan and Uzbekistan), the Caspian Sea (Kazakhstan, Russia, Azerbaijan, Iran, and

Turkmenistan), Lake Urmia (Iran), Lake Issyk-Kul (Kyrgyzstan), Walker Lake (USA), Salton Sea (USA), and Mono Lake (USA).[1]

As terminal lakes shrink and desiccate, they become hotspots for dust emissions. Some terminal lakes have experienced decreased inflows as a result of climate change; however, increasing demands on the water for human use represent the major factor in the decline of terminal lakes.[3] For example, the Aral Sea in Central Asia has been reduced in area by three-quarters and in water volume by 90% primarily due to agricultural water use.[2] In the Unites States, Owens Lake was desiccated due to water diversions to Los Angeles, California.[2] In Iran, Lake Urmia's area has been reduced by 69%. Researchers estimate that one-third of this decline in lake levels is due to climate change and climate models for the area predict increasing temperatures and decreasing precipitation by 2050.[3] Moving into the future, drought and increasing temperatures associated with climate change are a serious threat to terminal lakes because of decreases in runoff and the increased demand for irrigation water to grow crops in a warmer climate.[3]

Dust emissions from drying terminal lakes produce fine particulate matter ($PM_{2.5}$) air pollution. For example, the dry lake bed of Owen's Lake is a source of $PM_{2.5}$ that causes exceedances of national air quality standards.[2] This lake bed in California's Owens Valley produces the most dust pollution of any site in the United States.[3] Dust mitigation costs have exceeded the economic value of the diverted Owens Lake water.[2] As another example, at the Salton Sea in California, each 1-foot (0.35-m) drop in lake elevation led to a 2.6% increase in annual average (long-term) $PM_{2.5}$ in the counties surrounding the lake.[4] Extreme events such as dust storms can also dramatically elevate short-term atmospheric $PM_{2.5}$ dust concentrations. Indeed, wind-driven dust storms from the dry lake bed at the Salton Sea have impacted the air quality in surrounding communities.[5,6] Worldwide, the last decade has witnessed more frequent dust storms, with dust concentrations predicted to increase in the coming decades due to climate change.[7]

$PM_{2.5}$ is the leading environmental cause of human mortality worldwide,[8] and responsible for $\sim$50,000 premature deaths annually in the United States.[9] Dust $PM_{2.5}$ exposures specifically are well-established health risk factors; a scoping review of 204 studies found that 85% of those studies reported a statistically significant association between dust and health effects, most commonly respiratory and cardiovascular morbidity and mortality.[10] Dust exposures are also associated with infectious and non-infectious diseases, including influenza A, pulmonary coccidioidomycosis (valley fever), bacterial pneumonia, meningococcal meningitis, chronic obstructive pulmonary disease, asthma, sarcoidosis, and pulmonary fibrosis.[7] While the majority of dust health studies have been conducted in the Middle East and Asia,[11–13] studies in the United States have found linkages between dust storms and human health conditions, including coccidioidomycosis,[14] asthma, and bronchitis.[15] While few studies have documented human health effects of drying lakes to date, researchers in California documented excess respiratory mortality due to $PM_{2.5}$ from the drying Salton Sea between 1998 and 2014 in the counties surrounding the lake.[4]

Negative health effects due to short-term, episodic $PM_{2.5}$ exposures (i.e., hours to days) are well understood[16]; however, social disparities in those exposures have received little attention (for exceptions, see[17,18]). Research has instead examined, and consistently documented, long-term (months-to-years) $PM_{2.5}$ exposure disparities nationwide based on racial/ethnic minority and low socioeconomic statuses,[19–21]. One U.S. national study has documented even larger racial/ethnic disparities in short-term vs. long-term $PM_{2.5}$ exposures.[17] Previous work along the urban Wasatch Front, which is adjacent to the shrinking GSL and where 80% of Utah's population resides, reports both long-[22] and short-term[18] $PM_{2.5}$ exposure disparities by race/ethnicity. Research also identifies differences in trace heavy metal deposition at eight sites based on race/ethnicity and income.[23] While there is little work on disparities in short-term exposures,[17,18] to the best of our knowledge, social disparities in $PM_{2.5}$ exposures from dust storms have yet to be assessed.

The GSL in Utah is the largest terminal lake in the Western Hemisphere (and the eighth largest in the world); like many of its counterparts worldwide, it has experienced desiccation in recent decades.[1] The GSL dropped to a record low of 1,276.7 m above sea level (mASL) in November 2022 following a multi-decadal decline in lake levels. Over the past several thousand years, the GSL has fluctuated around a long-term water elevation of around 1,280 mASL.[24] The GSL experienced its historical high in the mid-1980s and has since steady declined, driven primarily by human water depletions upstream with secondary contributions from decreased precipitation (e.g., multiple very dry years) and anthropogenic climate change that increases evapotranspiration rates.[3,25]

Concerns about a vanishing GSL are multifaceted and have risen to national prominence in recent years. In June 2022, *The New York Times* likened the drying GSL, the surface area of which has shrunk by two-thirds, to a "environmental nuclear bomb." The shrinking GSL has raised concerns about arsenic pollution, the loss of flies and brine shrimp habitat imperiling 10 million migratory birds that feed on them, and reduced lake effect snow and accelerated snowmelt rates in adjacent mountains,[26,27] which would undermine the ski industry.[28] Dust plumes from the lake bed have potentially increased in severity and frequency as lake levels have fallen, constituting a serious public health concern. Dust emissions are physically related to the lake level, with higher lake levels decreasing the area of exposed lake bed and reducing the potential for emissions of dust.[25] In the absence of immediate action to deliver substantially more water to the lake, levels are expected to continue to decline and further expose lakebed to atmospheric weathering and wind, which will exacerbate dust emissions. While the spring 2023 season brought a slight reprieve as the GSL rose by 1 m due to recording-breaking precipitation and snowpack depths in the Wasatch Mountains,[29] future climate change is expected to amplify GSL water loss as increasing temperatures drive elevated evapotranspiration rates,[29,30] a fate similar to what is expected for terminal lakes globally.

Here, we specifically examine the GSL as a case study with relevance to drying saline lakes globally. We estimate social disparities in dust $PM_{2.5}$ exposures based on four policy-relevant water-level scenarios for a tri-county study area surrounding the GSL. We find disparities based on race/ethnicity and education levels, but not based on household income or housing tenure. Those existing disparities are predicted to attenuate if

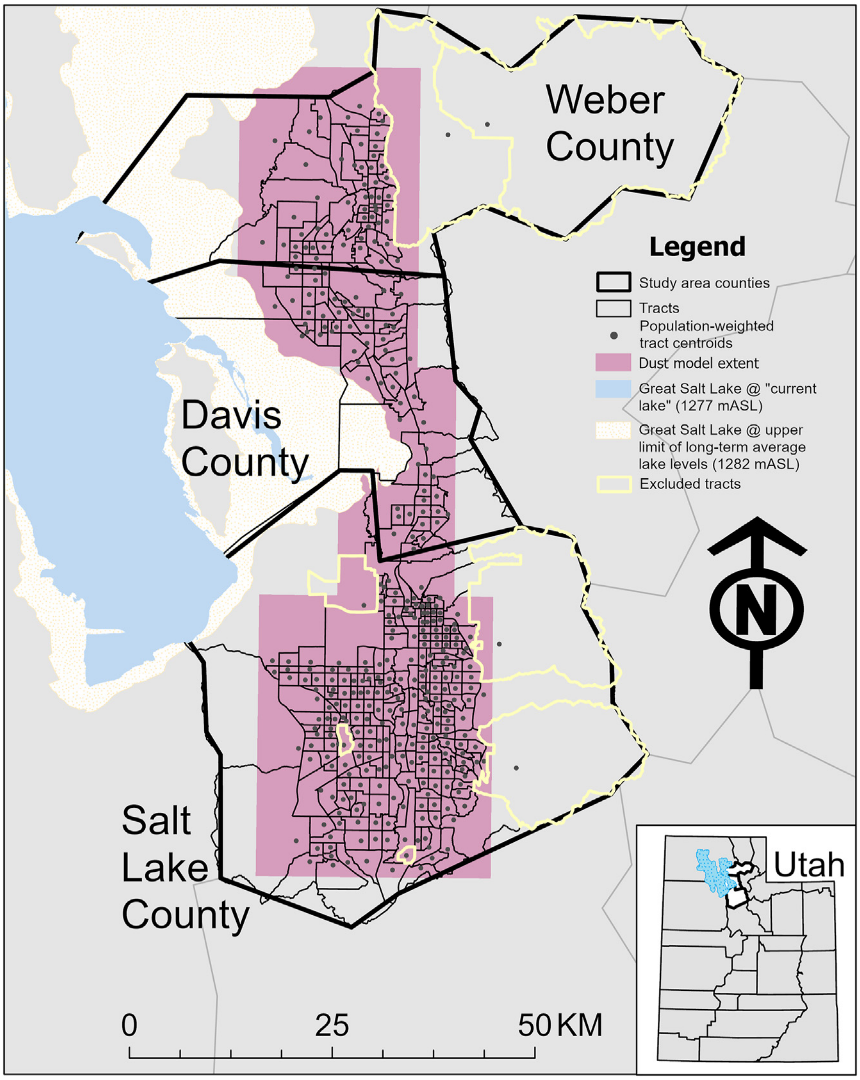

Figure 1. Study area map

Map of 2020 census tract boundaries and population-weighted tract centroid locations in the tri-county study area overlaid on the "current lake" levels for GSL, as well as the upper limit of long term average GSL levels[25] and the dust model extent.

lake levels rise to a healthier range. While studies have documented how some future climate change impacts (e.g., sea level rise and storm surge) pose socially disparate risks,[31] no study to our knowledge projects how various climate change and environmental policymaking pathways can affect social disparities in dust-driven $PM_{2.5}$ exposure. Studying how future adaptation scenarios may impact social disparities clarifies ways in which present-day policy decisions may simultaneously foster equitable health outcomes and improved ecological conditions in a rapidly changing climate.

RESULTS

Methods summary

In this study of the three-county area proximate to the GSL, we examine how predicted population-weighted $PM_{2.5}$ exposures ($\mu g\ m^{-3}$) from dust events vary by race/ethnicity and socioeconomic status under four differing GSL water-level scenarios ranging from the hypothetical "no lake" to a "healthy lake level" that slightly exceeds the long-term average. We then explore how changes in predicted population-weighted $PM_{2.5}$ exposures ($\mu g\ m^{-3}$) from dust events vary by race/ethnicity and socioeconomic status under two potential pathways: (i) depletion (current levels to no lake) vs. (ii) refilling (current to healthy levels). To do so, we first estimated population-weighted mean exposures (PWMEs) to dust and changes in exposures for racial/ethnic and socioeconomic status groups. We then calculated absolute disparity metrics to assess exposure disparities for the groups with the highest and lowest exposures and changes in exposure. Our study area includes 2020 census tracts in Weber County, Davis County, and Salt Lake County, Utah ($n = 375$) (Figure 1). The three counties are aligned north-south downwind of the GSL and are home to 1.8 million people. We excluded seven tracts with missing data, leaving $n = 368$. Those seven tracts include <1% of the tri-county population as per the 2020 Decennial Census; four were excluded due their population-weighted centroid falling outside of the dust model domain and three were excluded due to missing socioeconomic status data.

To inform our analysis of social disparities in dust exposure, we first gathered sociodemographic data. We obtained counts of persons per census tract in the following race/ethnicity groups from the 2020 U.S. Decennial Census: Hispanic, non-Hispanic White, non-Hispanic Black, non-Hispanic Native American, non-Hispanic Asian, non-Hispanic Pacific Islander, and non-Hispanic other race/multiracial. From the 2021 5-year American Community Survey, we obtained estimated census tract-level counts of people (age ≥25 years) with less than a high school diploma or at least a high school diploma, occupied housing units with renter or owner occupants, and households with incomes of less than \$50,000 or \$50,000 or more. Table 1 provides descriptive statistics.

To estimate how fluctuating GSL water levels would impact dust exposures along the Wasatch Front, we combined an atmospheric transport model (HYSPLIT-STILT[32,33]) with a dust emission model (FENGSHA). See experimental procedures for modeling details. We simulated dust emissions and transport for all wind-blown dust events identified during the spring of 2022. Significant dust events occurred on April 19, 20, and 21, and May 7, according to measurements from a local air quality monitoring station maintained by the Utah Division of Air Quality,

Table 1. Descriptive statistics

	Sum[a]	Min.	Max.	Mean	SD	%
Race/ethnicity[b]						
Total	1,792,608					
Hispanic or Latino	318,870					17.8
Non-Hispanic White	1,272,373					71.0
Non-Hispanic Black	28,900					1.6
Non-Hispanic American Indian and Alaska Native	9,873					0.6
Non-Hispanic Asian	60,489					3.4
Non-Hispanic Native Hawaiian and Other Pacific Islander	25,318					1.4
Non-Hispanic other race or multiracial	76,785					4.3
Socioeconomic status[c]						
Total ≥25 years	1,106,827					
With a high school diploma or more	1,023,933					92.5
Without a high school diploma	82,894					7.5
Total occupied housing units	592,032					
Owner	414,515					70.0
Renter	177,517					30.0
Total households	592,076					
Household income ≥$50,000	431,961					73.0
Household income <$50,000	160,115					27.0
Dependent variables						
Dust levels (μg m^{-3})[d]						
No lake		15.66	54.85	31.86	6.52	
Low lake (1,275 mASL)		14.89	42.89	26.41	4.01	
Current lake (1,277 mASL)		14.57	42.39	25.68	3.93	
Healthy lake (1,280 mASL)		13.87	41.24	24.02	3.57	
Change in dust levels (μg m^{-3})						
Depletion pathway: current lake to no lake		0.99	23.46	6.19	3.88	
Refilling pathway: current lake to healthy lake		−4.26	−0.63	−1.66	0.66	

[a]Summed values derive from counting all group members living in included census tracts (n = 368) in the three-county study area. The sum pertains the count of the variable's universe. For race/ethnicity, this includes people of all ages. For education, the sum applies only those >24 years of age. It is households for the income sum, and occupied housing units for the housing tenure sum.
[b]Data source: 2020 Decennial Census.
[c]Data source: 2021 5-year American Community Survey Estimates.
[d]The $PM_{2.5}$ contributions include only dust sources and do not include $PM_{2.5}$ from other sources such as anthropogenic or wildfires. These values pertain to the population-weighted centroid of all census tracts in the study.

which observed elevated levels of $PM_{2.5}$ and PM_{10} coincident with strong winds (>10 ms^{-1}). Dust model simulations were generated for four different scenarios: no lake, very low lake, current lake, and healthy lake. See experimental procedures for detailed explanations justifying our analysis of these scenarios. The four scenarios are depicted in Figure 2.

We used these dust surfaces to create dependent variables at the census tract level. We extracted predicted dust concentration values (μg m^{-3}) at the population-weighted centroid of each census tract for each of the four scenarios. We then estimated the predicted change in dust in μg m^{-3} for each tract under the two pathways by subtracting one value from another. We calculated (1) predicted increase in dust moving from "current lake" to "no lake" and (2) predicted decrease in dust moving from "current lake" to "healthy lake." Descriptive statistics for these seven dependent variables are listed in Table 1.

Finally, we calculated predicted PWME and change in predicted PWME to dust $PM_{2.5}$ (in μg m^{-3}). To assess absolute disparities for each of the demographic categories, we calculated absolute disparity metrics[17,21] for the four scenarios. These metrics compare the highest and lowest exposure group relative to the category mean exposure. We consider disparities of ±5% to be substantive.[34] We also calculated proportional change in absolute disparities to examine if each pathway would widen or narrow disparities. See the experimental procedures for more details on the analysis methods. We also performed sensitivity analyses, which the experimental procedures section details.

Differences in dust exposure between the four scenarios

Table 2 reports results of predicted PWME to dust for the social groups under the different scenarios. Predicted exposures for

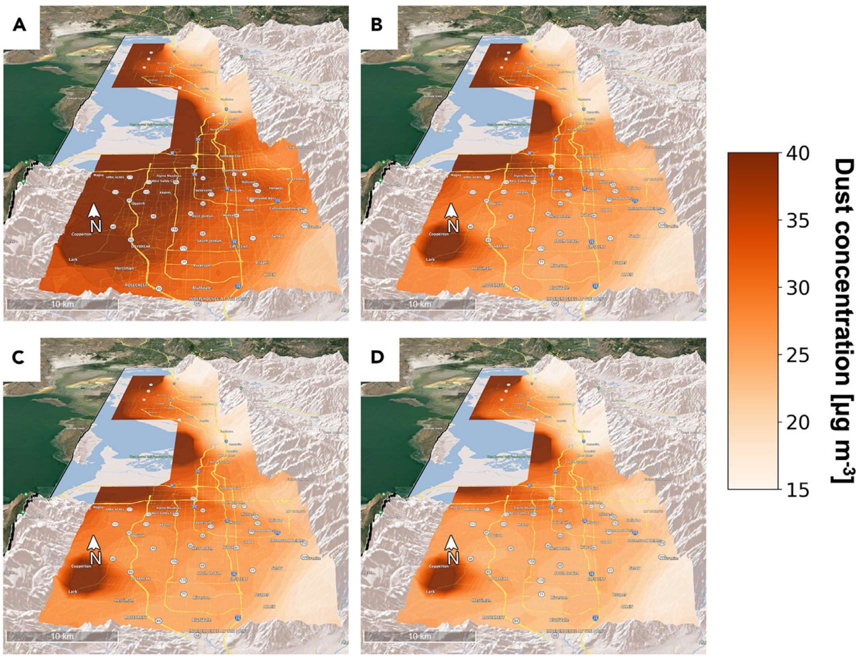

Figure 2. Gridded map of dust-contributed $PM_{2.5}$ concentrations for the study area

Gridded map of dust-contributed $PM_{2.5}$ concentrations (in µg m^{-3}) along the Wasatch Front using different GSL water level scenarios: (A) "no lake," (B) "very low lake" (1,275 mASL), (C) "current lake" (1,277 mASL), and (D) "healthy lake" (1,280 mASL). Dust amounts are averaged across all dust storms for the spring of 2022 and assume an erodibility fraction of 20%.

local residents decrease across the scenarios such that they are highest for the "no lake" (32.0 µg m^{-3}) and lowest for the "healthy lake" (24.0 µg m^{-3}) levels.

Racial/ethnic minority residents have higher predicted exposures than non-Hispanic Whites in all four scenarios and exposures are higher when lake levels are lower (Table 2). Pacific Islanders and Hispanics have the highest exposures. Pacific Islanders have predicted $PM_{2.5}$ concentrations of 36.4 µg m^{-3} (no lake) and 25.6 µg m^{-3} (healthy lake), while Hispanics have the second highest exposures, with 34.3 µg m^{-3} (no lake) and 24.9 µg m^{-3} (healthy lake). Exposures for Whites are lower, at 31.2 µg m^{-3} (no lake) and 23.7 µg m^{-3} (healthy lake). Specifically, at "no lake," the difference in µg m^3 between Pacific Islanders and Whites is 5.2; for Hispanics vs. Whites, the difference is 3.1. At "healthy lake," those differences narrow to 1.9 and 1.2 µg m^{-3}, respectively.

The absolute disparity in exposure between the highest and lowest exposed groups (compared with the category mean exposure) is 16.3% for race/ethnicity for the "no lake" scenario, and it drops to 7.9% at "healthy lake" (Figure 3). There is a general downward trend across the scenarios such that racial/ethnic disparities narrow as the GSL water level rises, yet all remain above 5%.

In terms of socioeconomic status (Table 2), the greatest difference between groups was based on educational attainment, with those lacking a high school diploma having predicted concentrations of 34.2 µg m^{-3} (no lake) and 24.9 µg m^{-3} (healthy lake) vs. those with a diploma having concentrations of 31.7 µg m^{-3} (no lake) and 23.9 µg m^{-3} (healthy lake). In other words, the difference in µg m^{-3} between those with and without a high school diploma decreases from 2.5 at "no lake" to 1.0 for "healthy lake."

The differences in PWME between disadvantaged and advantaged socioeconomic status groups were small (<1 µg m^{-3}) for income and housing tenure for all scenarios (Table 2). As per Figure 3, the absolute exposure disparity is 7.7% for education and less than 1.5% for income and housing tenure at "no lake." The education disparity in PWME narrows and then stays relatively constant at less than 5% for "very low lake," "current," and "healthy lake" levels (i.e., 4.2%, 4.4%, and 4.0%) as compared with "no lake" levels (7.7%).

Differences in dust exposure between the two pathways

Table 3 reports changes in predicted PWME for the social groups under the two pathways. If the lake stabilized at healthy levels consistent with conservation/policy action (refilling pathway), all social groups would experience lower dust concentrations relative to current lake levels (i.e., all values are negative, Table 3). The greatest decreases in dust are predicted for some of the socially disadvantaged groups (i.e., racial/ethnic minorities, those with no high school diploma, and renter occupants). The groups with the greatest decreases in dust across the analyses are Pacific Islander, Hispanic, and Black residents (2.0, 1.8, and 1.8 µg m^{-3}, respectively), as well as those with no high school diploma (1.8 µg m^{-3}). However, the decreases relative to the most advantaged group are small (e.g., <0.45 µg m^{-3} for the racial/ethnic groups).

Under the hypothetical depletion pathway, those expected to see the largest increases in dust exposure are groups disadvantaged based on race/ethnicity and education, while the magnitude of the predicted increase in dust is smaller for White and better-educated residents. In terms of race/ethnicity, the depletion pathway increases dust by 5.8 µg m^{-3} for non-Hispanic Whites, 7.5 µg m^{-3} for Hispanics, and 8.8 µg m^{-3} for Pacific Islanders. The increases in predicted dust exposure between housing tenure and income groups were negligible (<0.01 µg m^{-3}).

Table 3 also reports the proportional change in absolute disparities between scenarios included in the pathways for race/ethnicity and education. This is expressed as a proportion or ratio, where values above 1 mean that disparities are larger, and values under 1 indicate smaller disparities. Tenure and income are excluded from this analysis due the absolute disparities for all scenarios being between −5% and 5%. Under the refilling pathway, the proportional change in absolute disparity for race/ethnicity and education suggest narrowing disparities. The race-based disparity in exposure to dust would be 0.88 times smaller at "healthy lake" than "current lake." For education, the disparity would be 0.91 times smaller at "healthy

Table 2. Population-weighted mean predicted exposure to dust $PM_{2.5}$ in $\mu g\ m^{-3}$ by demographic group

	No lake (SE)	Very low lake (SE)	Current lake (SE)	Healthy lake (SE)
Race/ethnicity				
Total: All races	31.98 (0.005)	26.46 (0.003)	25.72 (0.003)	24.04 (0.003)
White	31.19 (0.006)	26.01 (0.004)	25.36 (0.004)	23.74 (0.003)
Hispanic	34.33 (0.013)	27.50 (0.007)	26.79 (0.007)	24.94 (0.006)
Black	33.68 (0.036)	27.50 (0.021)	26.76 (0.020)	24.92 (0.018)
Native American	33.38 (0.066)	27.30 (0.038)	26.58 (0.036)	24.80 (0.032)
Asian	33.36 (0.024)	26.99 (0.014)	26.26 (0.014)	24.47 (0.012)
Pacific Islander	36.42 (0.038)	28.42 (0.020)	27.67 (0.019)	25.64 (0.017)
Other race	31.92 (0.023)	26.49 (0.014)	25.76 (0.014)	24.08 (0.012)
Socioeconomic status: education				
Total: Age ≥25	31.90 (0.006)	26.37 (0.004)	25.65 (0.004)	23.98 (0.003)
High school diploma	31.72 (0.006)	26.29 (0.004)	25.56 (0.004)	23.91 (0.004)
No high school diploma	34.17 (0.025)	27.41 (0.013)	26.70 (0.013)	24.88 (0.011)
Socioeconomic status: tenure				
Total: Occupied housing units	31.81 (0.008)	26.38 (0.005)	25.65 (0.005)	23.99 (0.005)
Owner	31.68 (0.010)	26.25 (0.007)	25.53 (0.006)	23.88 (0.006)
Renter	32.12 (0.014)	26.67 (0.008)	25.93 (0.008)	24.26 (0.007)
Socioeconomic status: income				
Total: Households	31.81 (0.008)	26.38 (0.005)	25.65 (0.005)	23.99 (0.005)
Higher income (≥$50,000)	31.73 (0.010)	26.29 (0.006)	25.55 (0.006)	23.90 (0.005)
Lower income (<$50,000)	32.05 (0.016)	26.62 (0.010)	25.90 (0.009)	24.25 (0.008)

lake" than "current lake." Under the depletion pathway, the changes in absolute disparities for race/ethnicity and education are indicative of widening disparities. Race-based disparities at "no lake" would be 1.8 times greater than they are at "current lake" levels. Education-based disparities would be 1.7 times greater.

DISCUSSION

The predicted $PM_{2.5}$ dust concentrations for all groups have the potential to be detrimental to human health, as the concentration levels are above the 24-h World Health Organization threshold (15 $\mu g\ m^{-3}$). However, predicted exposure for all groups except Pacific Islanders is below the less stringent U.S. National Ambient Air Quality Standards (NAAQS) for 24-h averaged $PM_{2.5}$ (35 $\mu g\ m^{-3}$).[17] Exposures under U.S. NAAQS are still associated with deleterious health effects.[35] In addition to wind-driven dust exposures, community residents also face exposures from other sources of $PM_{2.5}$, e.g., traffic pollution, wildfire smoke, and industry.[36] In light of our prediction that dust $PM_{2.5}$ concentrations would be 7.9 $\mu g\ m^{-3}$ lower under a "healthy lake" vs. "no lake" scenario for the average Wasatch Front resident, we conclude that concerted efforts to stabilize the GSL at a healthy level will reduce the health risks of dust exposures, although there are other local sources of dust, especially in urban areas.[23]

While all Wasatch Front residents face potentially unhealthy levels of dust exposure, our estimates reveal clear exposure disparities based on race/ethnicity, and for Pacific Islander vs. White residents in particular. Pacific Islanders' disparate contemporary exposures in particular reflect their historical marginalization to the northwest, near the GSL. This happened as more powerful White settlers excluded them from desirable eastern Salt Lake Valley locations with fresh water streams and arable land adjacent to the Wasatch Mountains.[37] Contemporary residential patterns were initiated in the late 1800s with the removal of the first Pacific Islander settlers from the Salt Lake Valley to the colony of Iosepa in the Skull Valley to the west (present-day Tooele County). While Iosepa was abandoned due to its inhospitable environmental conditions, the pattern of Pacific Islander settlement within the study area's western and northern reaches near the GSL was initially established more than a century ago.[37]

In terms of the magnitude of predicted exposure disparities, differences between racial/ethnic groups range from 1 to 5 $\mu g\ m^{-3}$ across all scenarios. Small increases in $PM_{2.5}$ concentrations may have significant health effects,[8] especially at relatively low levels of exposure.[38] Other studies in Salt Lake County examining social disparities in $PM_{2.5}$ during short-term winter inversions[18] and based on long-term average concentrations[22] have also found disparate exposure for minoritized racial/ethnic groups. Similar to our findings, those studies found race/ethnicity to be more strongly associated with $PM_{2.5}$ exposures than socioeconomic status.[18,22] Those social disparities in dust exposure align with findings from the environmental justice literature. People of color and lower socioeconomic status in the United States and globally are disproportionately impacted by deleterious environmental health conditions relative to their White and higher-socioeconomic status counterparts. These groups, often marginalized within residential areas segregated by race/ethnicity as well as socioeconomic status, are disproportionately exposed to toxic waste sites and dumping,

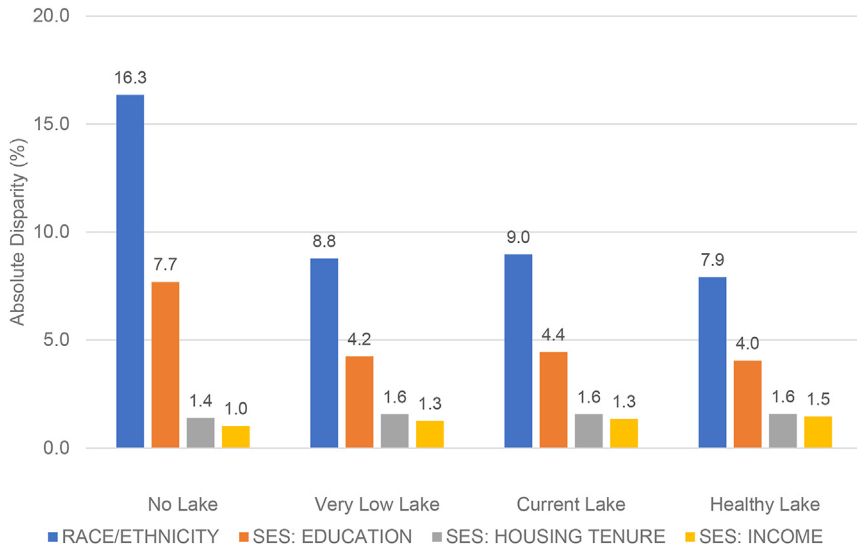

Figure 3. Absolute disparity metrics for each lake level scenario

Absolute disparity metrics (unit: percent) comparing degree of inequality between highest and lowest predicted PWME groups for each lake level scenario. As per Table 2, those groups with the highest PWMEs were Pacific Islander, no high school diploma, renter, and lower income. The groups with the lowest exposure were White, high school diploma, owner, and higher income. SES, socioeconomic status. The values reported in Figure 3 were calculated from PWME reported in Table 2 but at three significant digits and then rounded.

industrial pollution, urban heat,[39–41] and various sources of air pollution (e.g., from industry to private transportation).[17,20,42]

Decreases in $PM_{2.5}$ dust concentrations attributable to coordinated policy responses that stabilize the GSL at a healthy level, as opposed to allowing lake levels to decrease even further, may have the environmental justice co-benefit of attenuating current dust exposure disparities for minoritized racial/ethnic groups. Hypothetically allowing GSL lake levels to drop from current levels to no lake (depletion pathway) would result in changes in absolute disparities that heighten environmental injustices with respect to race/ethnicity and education. If GSL water levels were stabilized at healthy levels compared with allowing the GSL to desiccate (the refiling pathway), those injustices would be slightly dampened. When comparing proportional change in absolute disparities at the extreme scenarios of "healthy lake" with "no lake," the disparity would become 2.1 times higher for race and 1.9 times higher for education. It is possible that, in addition to providing other benefits, stabilizing the GSL holds potential to promote environmental justice, as lake level stabilization may reduce dust exposures and exposure disparities in a context beset by pronounced underlying racial/ethnic disparities in $PM_{2.5}$ exposures.[18,22] Letting the lake desiccate would amplify existing environmental inequities. Environmental justice scholarship in the United States emphasizes disparities along lines of class and race/ethnicity, but future studies for terminal lakes globally could assess differences across other contextually-relevant social dimensions, such as religious minority status, gender, Indigeneity, age (children or elderly), migrant status, or disability.

While it is impossible to generalize from a single case study, we suspect that the patterns of changes in disparities uncovered here will be present in other cases of terminal lakes, at least in the United States. Existing scholarship on environmental justice has established that disparities in exposure to pollution are remarkably consistent across a range of geographic contexts, so it is plausible to expect other U.S. terminal lakes to exhibit similar patterns. Scholars have identified two general mechanisms that typically produce these environmental inequalities.[39] In some cases, disadvantaged groups settle on land that is disproportionately exposed to industrial pollution or other hazards because it is less desirable and thus cheaper. This is the case on the West Side of the Salt Lake Valley, where anthropogenic sources of $PM_{2.5}$ cluster, property values are relatively low, racial/ethnic minority groups concentrate, and exposed areas of the dry GSL bed are nearby.[22] In other cases, historic discrimination has marginalized disadvantaged groups within undesirable residential areas, including those exposed to air pollution. This is the case in historically redlined areas of Salt Lake City, which were inhabited by "laborers" and "foreigners" during the Great Depression.[22] These historically redlined areas are all located on the West Side, where racial/ethnic minority residents are over-represented and exposures to $PM_{2.5}$ from a variety of sources (GSL dust, petrochemical industry, road traffic) are high,[22] a pattern reflected across U.S. cities.[43] Given the strength of these patterns across the United States and different environmental hazards, it is probable that low-income and racial/ethnic minorities are more exposed, on average, to dust storms across the country. We also expect that adaptation policies would change exposure disparities to other threats, such as flooding from sea level rise or wildfires. Since some groups are more exposed than others to environmental hazards, policies to reduce exposure will likely disproportionately benefit low-income and racial/ethnic minority people. Future studies, however, are needed to assess the generalizability of these patterns.

With knowledge of the myriad benefits of raising the GSL water level—in terms of promoting ecological health, human health, and environmental justice—local researchers and policymakers are working to design and implement policy responses. A recent synthesis estimated water inputs needed get the GSL to heathy lake levels within 5 years (which would require inflows of 2,807 KAF [1,000-acre feet]/year), 10 years (2,348 KAF/year), and 30 years (2,145 KAF/year). They concluded that extremely aggressive conservation measures could get the lake to "healthy levels" within 5 years.[29] Implementing a multi-pronged approach is important. This could involve investing in new water-efficient mining technologies that would reduce GSL water depletions from current mining operations, optimizing agricultural water use to increase efficiency, engaging in water smart urban growth and municipal water conservation, and introducing tiered water prices and increased water metering.[25] Promising conservation practices include installation of drip irrigation where possible, laser leveling of fields and precision irrigation techniques, use

Table 3. Changes in population-weight mean exposure to dust under each pathway

	A: refilling pathway: current lake to healthy lake	A: depletion pathway: current lake to no lake	B: proportional change[a] in absolute disparity: refilling[b]	B: proportional change[a] in absolute disparity: depletion[c]
Race/ethnicity			0.88	1.82
Total: All races	−1.68	6.26		
White	−1.62	5.83		
Hispanic	−1.84	7.54		
Black	−1.83	6.92		
Native American	−1.78	6.81		
Asian	−1.79	7.10		
Pacific Islander	−2.03	8.75		
Other race	−1.67	6.17		
Socioeconomic status: education			0.91	1.73
Total: Age ≥25	−1.66	6.26		
High school diploma	−1.65	6.16		
No high school diploma	−1.82	7.47		
Socioeconomic status: tenure			N/A	N/A
Total: Occupied housing units	−1.65	6.17		
Owner	−1.65	6.15		
Renter	−1.67	6.20		
Socioeconomic status: income			N/A	N/A
Total: Households	−1.65	6.17		
Higher income (≥$50,000)	−1.65	6.17		
Lower income (<$50,000)	−1.65	6.15		

(A) Population-weighted mean change in exposure to dust $PM_{2.5}$ (in $\mu g\ m^{-3}$) by demographic group for each pathway and (B) Proportional change in absolute disparity metrics for each pathway. The absolute disparity numbers used in these calculations derive from the rounded values shown in Figure 3.

[a]In interpreting the numbers for proportional change in absolute disparity, numbers >1.0 reflect growing disparities, numbers <1.0 reflect shrinking disparities, and 1.0 would reflect no change between the two scenarios. Values of N/A mean that the absolute disparity of the inputs was ±5%. As there was no meaningful disparity for that demographic group, no further analysis was needed.

[b]This column reflects the proportional change in absolute disparity for the refilling pathway. It was calculated by taking absolute disparity for healthy lake PWME divided by the absolute disparity for current lake PWME.

[c]This column reflects the proportional change in absolute disparity for the depletion pathway and was calculated by taking absolute disparity for no lake PWME divided by the absolute disparity for current lake PWME.

of more water-efficient crops, water banking and/or split-season leasing (where farmers are paid to release part of their water allocation to the lake), and turf-grass removal and xeriscaping in municipal settings. Some funding has been allocated for these practices in the past several years by the Utah State Legislature, but additional funding, outreach, and scaling up of efforts is needed.[29] Ultimately, upstream water resources must be conserved and shepherded into the lake to realize ecological and health benefits.[25] Lake levels fluctuate with precipitation patterns so it is imperative to take advantage of wet years to increase water levels.[25]

There are limitations associated with our dust model projections. These include (1) a relatively small sample size (only a single dust season), (2) an assumption that all newly exposed GSL bed has homogeneous soil characteristics (i.e., playa with an erodibility fraction of 10% or 20%), (3) large uncertainties associated with threshold friction velocities, (4) an inability to account for effects of varying soil moisture, and (5) error of up to 6 $\mu g\ m^{-3}$ in our dust predictions, which limits our precision. We are also limited to using current sociodemographic data for small areas when examining the future dust scenarios based on GSL water levels and four tracts with ACS data were excluded due to their location outside the dust extent. These tracts are located on the eastern fringes of the urban area (relatively far from the GSL), at higher elevations (and would therefore have lower dust exposures), and they are Whiter than the rest of the study area as per the 2020 census; it is highly likely that including them in the analysis would have intensified the patterns observed in this paper.

Since the GSL is located in one of the fastest growing urban regions in the United States, it is likely that the populations impacted by GSL dust will continue to change and grow. Future studies could combine sociodemographic projections with ecological and policy scenarios to capture more precise dynamics. Moreover, the “no lake” scenario is physically unlikely due to stabilizing feedbacks of declining evaporation rates as lake surface declines, but is nevertheless useful in calculating the full potential range of outcomes for risk assessment.

Conclusions

The drying of the GSL is not unique, since desiccation of terminal lakes is a major ecological catastrophe of the twenty-first century.[1] Protection of terminal lakes demands policy actions to protect ecological and human health. As we found here, reductions in ambient dust exposures represent an important benefit of stabilizing terminal lakes at healthy levels, along with more equitably decreasing dust exposure risk across population groups (i.e., promoting environmental justice). Stabilizing water levels would likely reduce the health burden of dust storms[7,14,15] on populations living near such lakes globally. Our study also highlights the value of applying an environmental justice perspective to examine changes in patterns of exposure disparities under different adaptation pathways within the purview of policymaking using simple metrics that are readily accessible to stakeholders. Such an approach is applicable to other adaptation planning domains (e.g., urban greening or flood resilience initiatives). To summarize, our study demonstrates the importance of assessing how present-day policy options to protect ecological systems and the livelihoods they sustain may have important co-benefits of improving environmental health and reducing climate risks for marginalized social groups. In the context of the GSL, such an assessment approach clarifies actionable paths toward sustaining Earth's systems while promoting environmental health and justice.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for data should be directed to and will be fulfilled by the lead contact, Sara Grineski (sara.grineski@soc.utah.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data and code for the dust models have been deposited to Zenodo. The STILT trajectory model code used to automate and simulate the transport of dust can be downloaded at: https://doi.org/10.5281/zenodo.1238047. The code used to generate the dust emission model, along with the dust concentration fields, and input files have been archived under the https://doi.org/10.5281/zenodo.11130515. The output files described above are archived as geotiff formatted files and are georeferenced. The sociodemographic data are publicly available for download at https://data.census.gov/.

Dust modeling details

We combined an atmospheric transport model (HYSPLIT-STILT Version 5.1.0[32,33]) with a modified version of the of the FENGSHA[44,45] dust emission model to estimate how changes in GSL water levels would impact dust exposures along Utah's Wasatch Front. Backward trajectories from HYSPLIT-STILT were used to estimate the atmospheric transport pathways and resulting dust $PM_{2.5}$ concentrations on a 0.02° × 0.02° gridded mesh that covered the three-county study area. Backward trajectories were released from each grid cell on our gridded mesh at a height of 10 mAGL, which is an altitude roughly representing human exposure to dust. Backward trajectories were then used to derive an atmospheric "footprint" for each grid cell, which represents receptor sensitivity to upwind source regions.[33] The footprint for a given grid cell is a function of the number and time backward trajectories spend for a given grid cell below one-half of the planetary boundary layer height. The boundary layer height for the location of each trajectory is calculated based on vertical temperature and wind profiles from the meteorological analysis driving the backward trajectories. Vertical temperature and wind profiles are then used to calculate the modified Richardson number.[32,33] The atmospheric footprint HYSPLIT-STILT model simulations were automated using the STILT-R wrapper[33] (https://uataq.github.io/stilt). We convolved HYSPLIT-STILT atmospheric footprints with dust emissions to quantify near-surface dust concentrations along the Wasatch Front.[27,45] We generated an ensemble of 1,000 backward trajectories for each HYSPLIT-STILT simulation, where trajectories were simulated up to 24 h backward in time. Backward trajectories from HYSPLIT-STILT were driven by winds (~3-km grid spacing) provided by the high-resolution rapid refresh model (HRRR).[46] HYSPLIT-STILT model simulations were generated for every hour for each dust event during the spring of 2022.

Dust emissions (F) from FENGSHA were calculated by computing the difference between the friction velocity (u_*) and the threshold friction velocity (u_{*t}):

$$F = K \times A \times \frac{\rho}{g} \times SEP \times u_* \times \left(u_*^2 - u_{*ti,j}^2\right) x\, S_i \text{ for } u* > u_{*t}. \quad \text{(Equation 1)}$$

The threshold friction velocity determines the shear stress needed to loft soil particles into the atmosphere. The threshold friction velocity is dependent on the vegetation (i) and soil type (j), along with soil moisture. An additional modification was made to the FENGSHA dust emission model where a new soil type (playa), which represents dry lake beds, was added to the model. Here, grid cells that were associated with the playa soil type were assigned a threshold friction velocity of 0.34 ms^{-1} based on field experiment data for Owens Lake.[47] Adding playa to the FENGSHA dust emission model significantly improved dust model simulations across northern Utah.[45] Fluxes of dust are also dependent on ratio of the vertical flux to horizontal sediment (K),[48] the soil erodibility potential (SEP), air density (ρ), the gravity constant (g), and the supply limitation factor (A), which is set equal to 32. NASA's Global Land Data Assimilation System soil texture database (https://ldas.gsfc.nasa.gov/gldas) was used to estimate clay, silt, and sand fractions needed to calculate SEP.[44] Twenty percent of the flux of dust was assumed to be emitted as fine particulates with a diameter of 2.5 μm. Finally, the fluxes of dust were multiplied by the grid cell erodibility fraction (S_i), which is dependent on the land cover type. Vegetation coverage, land cover type, and soil type data were obtained from the 2017 National Land Cover Database and the U.S. Geological Survey (USGS). Friction velocities from the HRRR reanalyses were used as inputs for the FENGSHA dust emission model. A bathymetry dataset for the GSL from the USGS[49] was used to modify the size of the GSL within the dust emission model. Grid cells that were converted from water to dry lakebed were reclassified as playa and were assigned as having a land cover type of barren with no vegetation. Dust emissions were simulated on a 0.05° × 0.05° grid that covered the entire Western United States to capture local and regional sources of dust.[27,45]

Model simulations of dust during the spring of 2022 were evaluated with air quality stations within our model domain for current GSL water levels (1,277 mASL). As shown in Figure S1, model-predicted $PM_{2.5}$ concentrations from dust sources compared well with $PM_{2.5}$ air quality monitoring stations maintained by the Utah Division of Air Quality ($r = 0.68$, bias = 6.2 μg m^{-3}). It should be emphasized that the dust model does not account for other sources of $PM_{2.5}$, e.g., anthropogenic emissions, which can contribute another 2–5 μg m^{-3} of $PM_{2.5}$ for locations along the Wasatch Front.

Description and justification for four dust scenarios

We created four dust scenarios. First, to represent the maximum potential dust exposure from the GSL, we converted the entire GSL into exposed lakebed ("no lake" scenario). Second, we estimated dust with GSL lake levels at 1,275 mASL ("very low lake" scenario), which assumes low inflow (2018–2022 rates) and no conservation measures based on recent water budget syntheses.[25,50] Third, we estimated dust using average 2020–2022 GSL water levels of 1,277 mASL ("current lake" scenario). Fourth, we generated dust simulations for lake levels at 1,280 mASL ("healthy lake" scenario). We used this level as it is regarded to be the lower bound of a "healthy" GSL and the target for policy action. Specifically, the state's Great Salt Lake Commission reported in January 2024 that the lake is considered to be at a healthy level when it is at or above 4,198 feet (1279.55 mASL).[51] The Great Salt Lake Strike Team, a partnership of scientists from two state universities and state leads from the Utah Departments of Natural Resources, Agriculture and Food, and Environmental Quality, also asserted the same healthy lake target level in their recent report, emphasizing the importance of achieving this level by the 2034 Olympic and Paralympic Games.[29] The Utah Rivers Council uses 4,200 feet (1,280.1 mASL)[52] in their proposed legislation, research and reports as their healthy lake threshold. This level of approximately 1,280 mASL also corresponds with average GSL water levels between 1950 and 2010 and reflects the Utah Division of Forestry, Fire and State Lands' matrix analysis, which highlights that this lake level optimizes ecosystem, economic, and health benefits.[25] When modeling, we shut dust emissions off from grid cells classified as water and we classified areas of newly exposed lakebed as playa with an erodibility fraction of 20%, which is conservative. This percentage is conservative as other similar studies of dust from exposed playa at terminal lakes use higher fractions, e.g., 35% for playa across North America.[53]

Analysis methods

To calculate the PWME, we used the following formula: PWME = Σ (Group population in each tract × Exposure in each tract)/Σ (Group population in each tract). The disparity metrics that we used capture the percent difference relative to the total PWME for each set of social variables with the highest and lowest PWME using the formula: 100 × (highest PWME − lowest PWME)/total PWME. We did this for each of the four lake levels. Then, we also calculated proportional change in absolute disparities for the scenarios implicated in the two pathways for demographic categories for which there was at least one disparity of ±5% (i.e., race and education) in the applicable scenarios (i.e., no lake, current lake, healthy lake). For the refilling pathway, we divided the absolute disparity for healthy lake PWME by the absolute disparity for current lake PWME for both race and education. For the depletion pathway, we divided the absolute disparity for no lake PWME by the absolute disparity for current lake PWME for race and education. To interpret these ratios, values over 1 reflect growing disparities, values under 1 reflect narrowing disparities, and values of 1 represent no change in disparity between the two scenarios.

Sensitivity analyses

First, we ran a separate set of simulations where newly exposed lakebed was assumed to have a more conservative 10% erodibility fraction[54] instead of 20%. Descriptive statistics for dependent variables used only in sensitivity analyses are in Table S1. Results presented in Table S2 and S3 replicate results in Tables 2 and 3 and Figure 3, with the more conservative assumption of a 10% soil erodibility fraction. Associations in Table S2 follow a similar pattern to Table 2, but dust $PM_{2.5}$ concentrations are lower due to reduced soil erodibility. Results in Table S3 also follow a similar pattern to those presented in Table 3.

Second, we replicated the PWME and pathways analysis for the four scenarios (shown in Table 2 and Figure 3) and two pathways (shown in Table 3 and Figure 3) at 20% erodibility using two different income cut-offs to explore if our income results were sensitive to the break point used. Descriptive statistics for the income variables are shown in Table S4. PWME and pathways results are shown in Tables S5 and S6 and they follow a similar pattern to the income results in Tables 2 and 3 and Figure 3. We find very small differences in PWME between income groups no matter the break point used.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.05.006.

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AUTHOR CONTRIBUTIONS

S.G.: conceptualization; methodology; formal analysis; and writing-original draft. D.M.: data curation; methodology; formal analysis; and writing-review and editing. T.C.: data curation; methodology; writing-original draft; and writing-review and editing. M.A.: writing-original draft and writing-review and editing. J.L.: methodology and writing-review and editing. W.A.: writing-review and editing. K.P.: data curation and methodology.

DECLARATION OF INTERESTS

The authors report no conflicts of interest.

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