

# Association between Great Salt Lake desiccation, air quality, and major depressive episodes: an ecological study



Maheshwari Neelam, Kamaldeep Bhui, Trent Cowan, Brian Freitag



## Summary

**Background** The desiccation of the Great Salt Lake (UT, USA), driven by water use and diversion, has reduced water inflow and exposed vast areas of lakebed. Exposed lakebed can release airborne PM<sub>2.5</sub>, degrading air quality in surrounding communities. Previous research has established links between air pollution and mental health outcomes, but there is little research on the specific mental health effects of declining lake levels and associated dust exposure. We aimed to examine the association between Great Salt Lake water levels, PM<sub>2.5</sub> concentration, and major depressive episodes in the surrounding population.

**Methods** In this ecological study, we investigated relationships between Great Salt Lake decline, PM<sub>2.5</sub> exposure, and mental health outcomes across all Utah counties using hydrological, atmospheric, and epidemiological datasets between 2006 and 2018. These data included in-situ lake measurements (from the US Geological Survey), PM<sub>2.5</sub> from ground-based monitoring and reanalysis datasets (from MERRA-2 and AirNow network stations), the Social Vulnerability Index (from US Centers for Disease Control and Prevention), and records of major depressive episodes (from the Substance Abuse and Mental Health Services Administration). All datasets underwent quality control, variable preparation, and calculation of Z scores, and were harmonised both spatially and temporally. We calculated PM<sub>2.5</sub> exceedance days based on US Environmental Protection Agency and WHO thresholds for harms, namely more than 15 µg/m<sup>3</sup> and more than 35 µg/m<sup>3</sup>. Statistical analyses included Kruskal–Wallis tests for non-parametric group comparisons, followed by Dunn's post-hoc tests for pairwise comparisons. An ANOVA examined direct (main) and indirect (interaction) effects between factors, with F statistics measuring between-group versus within-group variance ratios.

**Findings** Great Salt Lake shrinkage was linked to poorer air quality, with decreasing lake area ( $r=-0.28$ ;  $p<0.0001$ ) and volume ( $r=-0.31$ ;  $p<0.0001$ ) associated with more PM<sub>2.5</sub> exceedance days. A dose–response relationship was found between depression severity and pollution exposure: individuals who had fewer high PM<sub>2.5</sub> exceedance days had very low depression scores, whereas those exposed to more exceedance days had high and very high scores (H 28.9574;  $p<0.0001$ ). This relationship showed nuanced differences across seasons (H 152.4771;  $p<0.0001$ ) and age groups (H 51.8269;  $p<0.0001$ ). Finally, our analysis showed a direct association between PM<sub>2.5</sub> exceedance days and depression severity (F 12.341;  $p=0.0005$ ), whereas social vulnerability acted as a significant moderator (F 6.979;  $p=0.0084$ ). This interaction indicates that for a given level of PM<sub>2.5</sub> exposure, socially vulnerable populations have a disproportionately higher prevalence of major depressive episodes.

**Interpretation** This study found associations between PM<sub>2.5</sub> exposure and depressive episodes are concerning and warrant further longitudinal investigations, including more precise exposure measurements. Our findings underscore the complex interconnections between environmental degradation, air quality deterioration, and population mental health. By establishing this desiccated air pollution to mental health association, our results show that preventing lakebed exposure is not only an ecological necessity but a crucial public health intervention. Public health protections should focus on proactive watershed management alongside targeted mental health support for the most affected downwind and socially vulnerable communities.

**Funding** US National Aeronautics and Space Administration.

**Copyright** © 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## Introduction

The Great Salt Lake, located in northern Utah in western USA (41.1667°, -112.5833°; figure 1A), is the largest saltwater lake in the western hemisphere and the fourth largest terminal lake globally.<sup>1</sup> However, sustained water diversions and climate variability have led to rapid decline in the past few decades, with the lake losing approximately

73% of its volume and exposing 60% of its lakebed by 2023. This shrinkage poses important economic risks, with potential annual losses estimated between US\$1.7 and \$2.0 billion. However, these estimates do not account for the broader environmental hazards affecting surrounding communities.<sup>2</sup> As lakebed sediments are increasingly exposed and eroded, wind-blown dust, including fine

Lancet Planet Health 2026

Published Online  
<https://doi.org/10.1016/j.lanplh.2025.101405>

Universities Space Research Association, Huntsville, AL, USA (M Neelam PhD); CHIMES Research Group, Department of Psychiatry, University of Oxford, Oxford, UK (K Bhui MD FRCPsych); Department of Atmospheric and Earth Science, University of Alabama in Huntsville, Huntsville, AL, USA (T Cowan MSc); Marshall Space Flight Center, NASA, Huntsville, AL, USA (B Freitag PhD)

Correspondence to:  
Dr Maheshwari Neelam, Marshall Space Flight Center, NASA, Huntsville, AL 35805, USA  
[maheshwari.neelam@nasa.gov](mailto:maheshwari.neelam@nasa.gov)

### Research in context

#### Evidence before this study

This study was conceptualised and done in 2024. We systematically searched Web of Science, PubMed, and Google Scholar for peer-reviewed literature examining links between inland lake desiccation and mental health outcomes. Search terms were “lake drying”, “desiccation”, “drought”, “shrinking lake”, “dust storm”, “terminal lake”, “air quality”, “mental health”, “depression”, “anxiety”, “psychological impacts”, and “environmental water loss”, with no language restrictions and from database inception to Oct 23, 2024. Of 142 records identified, none met the inclusion criteria of directly investigating the relationship between lake desiccation and mental health. Existing literature focuses on physical health risks, such as respiratory disease and cardiovascular complications from dust storms and particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) exposure at locations such as Owens Lake (CA, USA) and Salton Sea (CA, USA). One systematic review reported that 41% of individuals near the drying Aral Sea (Kazakhstan and Uzbekistan) expressed concerns about their mental wellbeing, but this was based on self-reported symptoms and not direct, long-term epidemiological linkage to particulate matter exposure. In contrast, a complementary search of air pollution and mental health on Web of Science, PubMed, and Google Scholar, with terms “PM<sub>2.5</sub>”, “distress”, “suicide”, “wellbeing”, “mental health”, “psychological impacts”, “depression”, and “anxiety”, yielded 2847 results, with 156 meeting inclusion criteria. These studies, including multiple systematic reviews and meta-analyses, consistently found associations between particulate matter exposure and increased risks of depression, anxiety, and suicide. However, no studies have specifically examined the mental health effects of particulate pollution originating from desiccated lakebeds, despite mechanistic plausibility and growing relevance under a rapidly changing climate and depleting water resources.

#### Added value of this study

To our knowledge, this is the first ecological analysis to test the hypothesis that PM<sub>2.5</sub> exposure stemming from dry lakebeds is associated with depressive symptoms. Using county-level data across decades and multiple variables in Utah (USA), we found that days with PM<sub>2.5</sub> concentrations higher than WHO 24-h guidelines were associated with a higher prevalence of major depressive episodes. This association was consistent across counties with diverse social, demographic, and geographical profiles. The findings highlight a previously under-recognised and preventable environmental health pathway, stemming from regional hydrological decline. Further cohort studies and mechanistic research are needed to establish causality, inform mitigation strategies, and guide climate-resilient resource management.

#### Implications of all the available evidence

Our findings indicate that the mental health effects of environmental degradation from exposed lakebeds resulting from water diversion and hydrological decline remain under-recognised in environmental health research and policy. As freshwater resources decline and population pressures increase, particularly in arid and semi-arid regions, dust storms and desiccated lakebeds have become major sources of airborne fine particulate matter, contributing to both physical and psychological health burdens. Integrating environmental degradation, air quality, and community mental wellbeing into public health frameworks is increasingly essential to address these intersecting challenges. By providing policy makers with evidence for informed and holistic water management decisions, this research could open new avenues to simultaneously address environmental and public health concerns.

particulate matter (PM), is transported into populated areas, degrading air quality and increasing exposure to harmful aerosols. According to WHO guidelines, PM is categorised into PM<sub>2.5</sub> (defined by aerodynamic diameters of  $\leq 2.5 \mu\text{m}$ ) and PM<sub>10</sub> (defined by diameters of  $\leq 10 \mu\text{m}$ ).<sup>3</sup> The adverse health effects associated with PM are driven by a combination of particle size, concentration, chemical composition, and biological content, all of which can lead to inflammation in the body and brain.

A study by Cowley and colleagues<sup>4</sup> revealed that exposure to Great Salt Lake dust can cause airway inflammation and increased mucus secretion, exacerbating respiratory conditions more significantly than coal dust. The magnitude of this environmental challenge is similar to that found at Owens Lake (CA, USA), which the US Environmental Protection Agency (EPA) has classified as the nation’s largest single source of particulate matter.<sup>5</sup> Studies of similar hypersaline environments, such as Lake Urmia (Iran) and the Salton Sea (CA, USA), have reported substantial health

effects associated with salt dust exposure. Near Lake Urmia, hypertension prevalence in one county rose from 2.1% in 2012 to 19.5% in 2019, particularly affecting adults aged 50–70 years and females.<sup>6</sup> Research on the Salton Sea indicated that each 1-foot drop in lake elevation between 2008 and 2014 was associated with around one to 15 additional respiratory deaths per year in surrounding communities.<sup>7</sup> There is substantial evidence linking both short-term and long-term PM<sub>2.5</sub> exposure<sup>8</sup> to chronic obstructive pulmonary disease,<sup>9</sup> asthma, and bronchitis, recurrent lung infections, pulmonary insufficiency,<sup>10</sup> and cardiovascular diseases,<sup>11</sup> underscoring the far-reaching effects of exposed lakebeds beyond immediate air quality concerns.

In addition to the established effects of PM<sub>2.5</sub> on cardiovascular and respiratory health, there is emerging evidence that exposure to air pollutants could lead to neurocognitive disorders and affect mental health (directly and indirectly) through a range of potential causal pathways.<sup>12–14</sup> The mechanisms behind these effects are complex, involving

neuroinflammation and oxidative stress triggered by particulate matter that can cross the blood–air barrier of the lungs, gaining access to peripheral circulation and affecting multiple brain regions.<sup>15</sup> The biological component (a mixture of bacteria, viruses, and fungi) of particulate matter, known as bioaerosols, is associated with chronic and acute respiratory illnesses through various allergic and non-allergic mechanisms. Of particular concern are airborne cyanotoxins, including neurotoxins produced by naturally occurring cyanobacteria in the Great Salt Lake, which can become airborne as lakebeds are exposed and dispersed by winds to nearby populated areas.<sup>16</sup> Although current levels might not cause acute toxicity, long-term exposure could lead to chronic toxicity and potential neurological effects, including Lou Gehrig’s disease.<sup>17</sup> The risk is further compounded by the possibility of synergistic neurotoxicity, in which multiple toxins amplify each other’s effects. For instance, in a systematic review, Zundel and colleagues<sup>18</sup> consistently associated air pollution with neurostructural and neurofunctional effects, including changes in neurotransmitters, neuromodulators, and their metabolites, with these effects observed across various brain regions. Such causal studies are still scarce due to confounding influences such as noise, previous medical conditions, socioeconomic status, and little mental health data, undermining confidence about the direct causal inference.

This study uses a novel and interdisciplinary approach, exploring the potential mechanism for depression through poor air quality driven by lake loss, which has not been considered previously and could be responsive to preventive interventions.

## Methods

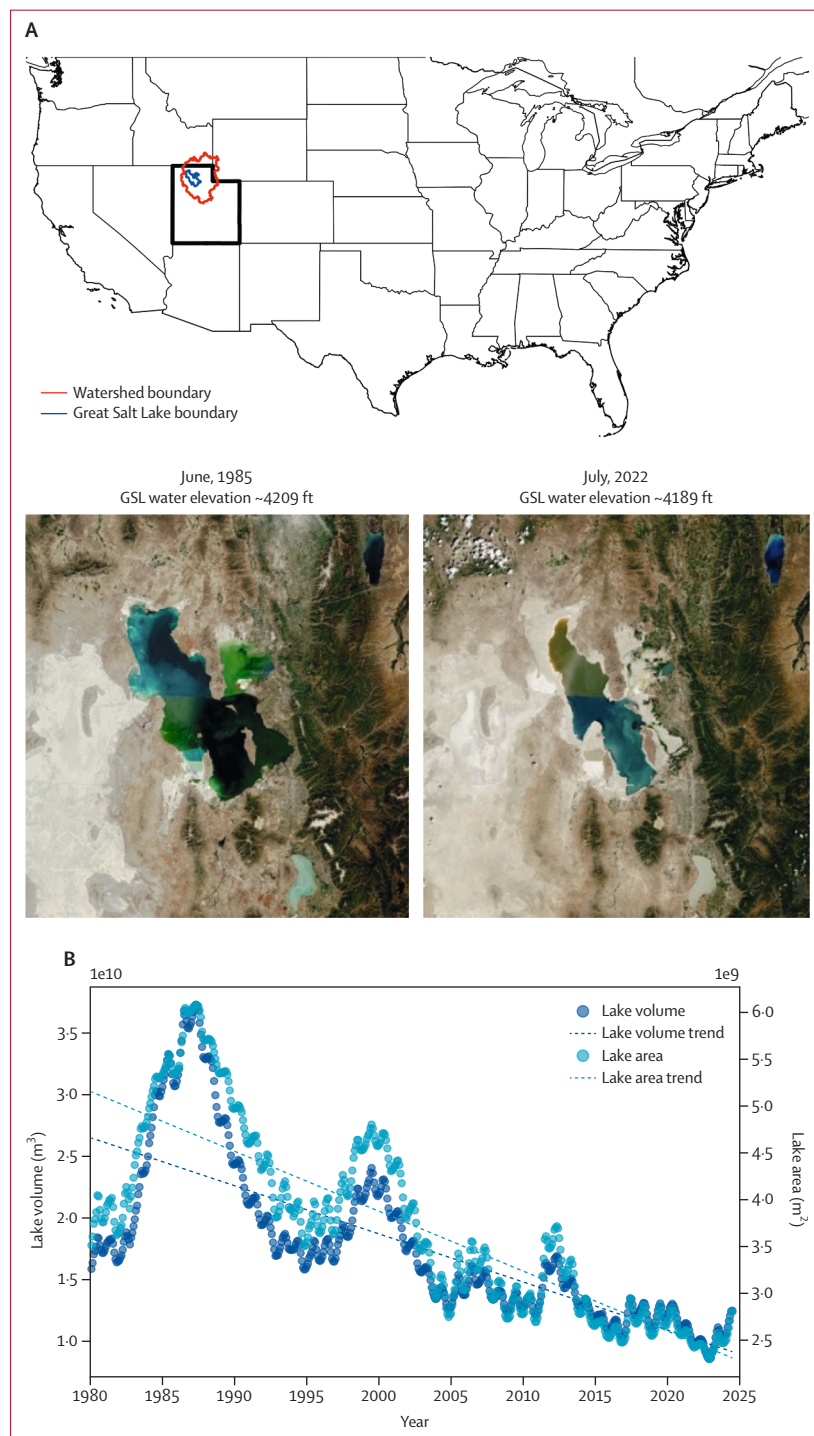
### Study design

In this ecological study, we used data on Great Salt Lake level, area, and volume and surrounding air quality metrics to investigate associations between lake desiccation and mental health outcomes in Utah (USA) from 2006 to 2018.

### Data sources

To quantify the lake’s decline, we used US Geological Survey in-situ measurements of lake level, area, and volume from Oct 18, 1847, to June 24, 2024, providing crucial historical context and study period decline.<sup>19</sup> Land cover dynamics within the watershed boundary were evaluated with the National Land Cover Database (2000–22) from the Multi-Resolution Land Characteristics Consortium.

For air quality studies, Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)<sup>20</sup> data was combined with ground-based measurements, including those from the EPA’s AirNow network stations within the Great Salt Lake watershed. This combination and synthesis of evidence allowed us to thoroughly analyse air quality trends and exceedances of air quality standards.



**Figure 1: Changes to Great Salt Lake from 1980 to 2022**

(A) Location of Great Salt Lake (41°1667′, –112°5833′) in northern Utah, western USA, and time-lapse imagery from remote sensing platforms in June, 1985 (US Landsat 5) and July, 2022 (Copernicus Sentinel-2), illustrating the progressive drying of the Great Salt Lake over the past four decades. (B) US Geological Survey measurements of Great Salt Lake area and volume over the past four decades.

For the **Multi-Resolution Land Characteristics** see <https://www.mrlc.gov/>

For the **US Environmental Protection Agency's AirNow database** see <https://www.airnow.gov/>

See Online for appendix

MERRA-2 is a long-term reanalysis project developed by US National Aeronautics and Space Administration's Global Modeling and Assimilation Office,<sup>21</sup> providing meteorological and aerosol data from Jan 1, 1980, to Dec 31, 2024. MERRA-2 data are available at a high spatial resolution of  $0.5^\circ \times 0.625^\circ$  with 72 vertical levels and hourly temporal resolution. The dataset includes components necessary for deriving PM<sub>2.5</sub> concentrations (appendix p 3). For this analysis, we consider two key thresholds: EPA's National Ambient Air Quality Standards<sup>22</sup> 24-h PM<sub>2.5</sub> standard of 35 µg/m<sup>3</sup> and WHO's more stringent 24-h guideline<sup>23</sup> of 15 µg/m<sup>3</sup>. These standards are based on extensive scientific evidence linking PM<sub>2.5</sub> exposure to serious health risks, including heart attacks and premature death.

The US Centers for Disease Control and Prevention provides a Social Vulnerability Index (SVI), which is a comprehensive tool that assesses community resilience to external stressors through 15 key variables grouped into four themes: socioeconomic status, household composition and disability, minority status and language, and housing and transportation.<sup>24</sup> The methods for developing the SVI, as detailed by Flanagan and colleagues,<sup>25</sup> forms the foundation for many longitudinal studies of regional social vulnerability patterns. SVI scores range from 0 to 1, with higher scores indicating greater vulnerability. Complementing this dataset, the Substance Abuse and Mental Health Services Administration provides annual, de-identified, cross-sectional data on individuals who received mental health treatment in the USA. This dataset includes information on Major Depressive Episodes (MDEs), which are defined based on the criteria of the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition (DSM-5). An MDE is diagnosed when an individual reports at least five of nine specific symptoms during a 2-week period, with at least one symptom being depressed mood or loss of interest in daily activities. The data distinguish between lifetime MDE and MDE in the past year. This analysis considers different age groups, since the adult and youth measures for MDE are different due to differences in question wording. Age groupings follow the Substance Abuse and Mental Health Services Administration's standardised categories from the National Survey on Drug Use and Health (ie, 12–17, 18–25, and ≥26 years), which are based on key developmental and legal distinctions relevant to substance use and mental health.

### Outcomes

The primary outcome was the prevalence of MDEs. MDEs were defined according to DSM-5 criteria and categorised into five levels of severity (very low to very high) based on survey-year county aggregates.

Secondary outcomes were ambient air quality degradation, specifically the frequency of PM<sub>2.5</sub> exceedance days exceeding harm thresholds hydrological decline of the Great Salt Lake, measured by annual changes in water surface area and total volume; chemical composition of

particulate matter, specifically the surface mass concentrations of dust, sea salt, sulphate, organic carbon, and black carbon to isolate lake-derived sources; demographic and temporal variations in the PM<sub>2.5</sub> and MDE relationship, specifically differences across age groups (12–17, 18–25, and >26 years) and seasons (winter, spring, summer, and autumn); and effect modification by social vulnerability, measured via the SVI to determine how the association between pollution and mental health varies across different socioeconomic contexts.

### Statistical analysis

All datasets were standardised spatially to the county level and temporally to monthly or survey-year scales. PM<sub>2.5</sub> exceedance days were calculated with two thresholds (>15 µg/m<sup>3</sup> and >35 µg/m<sup>3</sup>) from EPA AirNow stations and aggregated by county. MERRA-2 PM<sub>2.5</sub> data were validated against AirNow means, with compositional analysis distinguishing Great Salt Lake dust from other sources. Extreme events and outliers were screened via Z scores. We calculated monthly means from US Geological Survey lake data to match MERRA-2, and biennial SVI and MDE data were aligned with corresponding PM<sub>2.5</sub> measures. Datasets were merged into a comprehensive county-level file. SVI and MDE were binned by quantiles from very low to very high. Descriptive statistics (means, medians, standard deviation, and counts) summarised PM<sub>2.5</sub> exceedances, whereas non-parametric Kruskal–Wallis tests assessed differences across SVI and MDE categories, followed by Dunn's post-hoc comparisons. The ANOVA tested group mean differences and interactions, evaluating both direct and combined effects of factors. Further details on data harmonisation and methods are provided in the appendix (p 4). All analyses were done with Python (version 3.14).

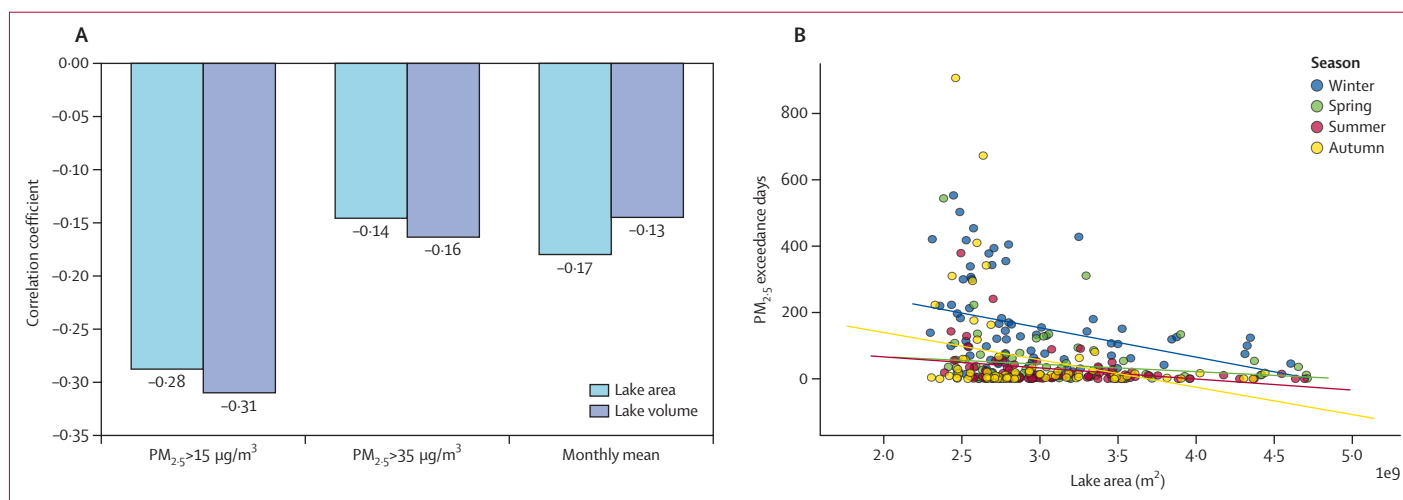
### Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

### Results

The Great Salt Lake had substantial declines in both total lake area and volume, as indicated by US Geological Survey gauges and National Land Cover Database, which also revealed evidence of lake desiccation (appendix p 2; figure 1). The lake area has been decreasing at a rate of 5.33 km<sup>2</sup>/month, equating to an annual reduction of about 64 km<sup>2</sup>, which represents roughly 1.7% of its mean area of 3731 km<sup>2</sup>. Similarly, the lake volume is declining at 32.52 million m<sup>3</sup> per month, translating to an annual loss of about 0.39 km<sup>3</sup> (390.27 million m<sup>3</sup>), or 2.2% of its mean volume of 17.82 km<sup>3</sup>. The analysis of PM<sub>2.5</sub> exceedance days from the EPA's AirNow stations and MERRA-2 data reveals significant negative correlations with the lake area and volume. The correlations are stronger with lake volume ( $r=-0.31$ ;  $p<0.0001$ ) than lake area ( $r=-0.28$ ;  $p<0.0001$ ; figure 2A). Seasonal variability is also evident, with the

For the **Substance Abuse and Mental Health Services Administration** see <https://www.samhsa.gov/node>



**Figure 2: Relationships between Great Salt Lake characteristics and PM<sub>2.5</sub> exceedance days**

(A) Pearson correlations between Great Salt Lake area and volume with PM<sub>2.5</sub> exceedance days (>15 µg/m<sup>3</sup> or >35 µg/m<sup>3</sup>) and MERRA-2 monthly means. (B) Seasonal variability in PM<sub>2.5</sub> exceedance days (>15 µg/m<sup>3</sup>) in relation to Great Salt Lake area.

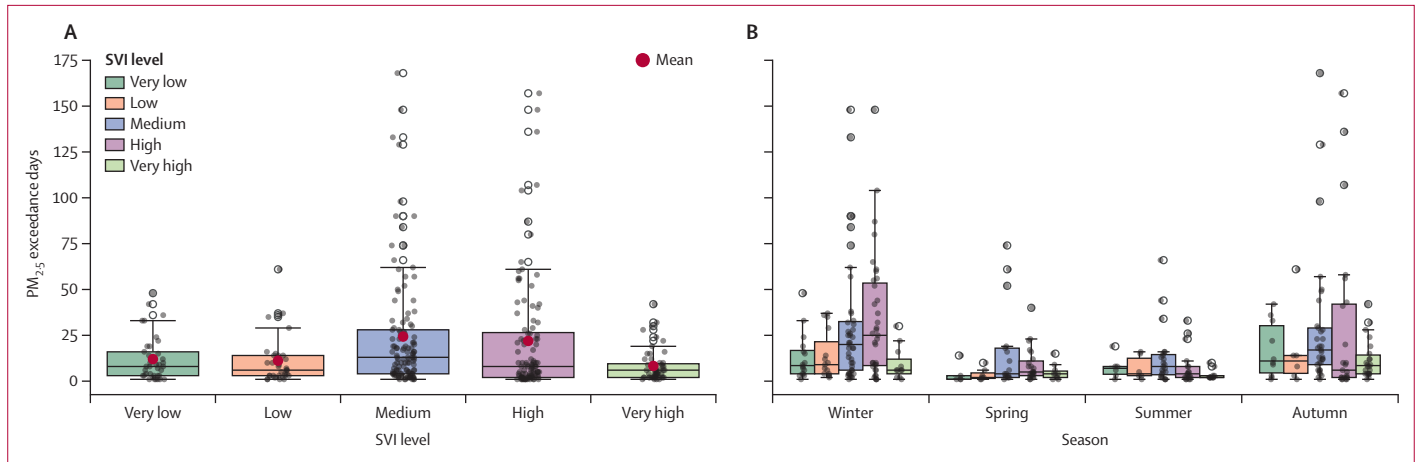
highest correlations observed during winter months (figure 2B). The compositional analysis of MERRA-2 PM<sub>2.5</sub> components from 1980 to 2023 reveals that dust surface mass PM<sub>2.5</sub> has substantially increased, contributing around 34.1% to total PM<sub>2.5</sub> concentrations (appendix p 3). Sea salt surface mass PM<sub>2.5</sub> accounted for around 3.2% of PM<sub>2.5</sub>. Sulphate surface mass concentration had a large decrease over time despite its contribution of around 34.9% to PM<sub>2.5</sub> concentrations (appendix p 3). Organic surface carbon mass has risen to contribute around 21.1% to PM<sub>2.5</sub> concentrations, whereas black carbon surface mass has slightly decreased to account for around 6.7% of PM<sub>2.5</sub> concentrations (appendix p 3). A substantial increase in PM<sub>2.5</sub> concentration has been observed from the 2000s, with a notable rise during the 2020s.

The Kruskal–Wallis test indicates statistically significant differences in PM<sub>2.5</sub> exceedance days in the SVI groups (H 19.3024; p=0.0007). Higher SVI groups (medium and high) had substantially more PM<sub>2.5</sub> exceedance days (>20 days) than the very low and low SVI groups (<13 days; figure 3A). However, the very high SVI group had fewer PM<sub>2.5</sub> exceedance days than the medium and high SVI groups. Seasonal variations within each SVI group were also evident (figure 3B; table 1). Overall, winter and autumn months generally had higher means across most SVI groups (table 1). The analysis of PM<sub>2.5</sub> exceedances greater than 35 µg/m<sup>3</sup> also reveals consistent patterns across SVI groups: the Kruskal–Wallis test found significant differences for PM<sub>2.5</sub> exceedances of greater than 35 µg/m<sup>3</sup> for SVI (H 14.7625; p=0.0052) and for MDE (H 21.1631; p=0.0003), although there was insufficient data for some seasonal subgroup analyses.

The Kruskal–Wallis test revealed statistically significant (H 28.9574; p<0.0001) differences in PM<sub>2.5</sub> exposure across MDE levels (figure 4A). The very low MDE group had a mean of 9.73 (SD 14.14) PM<sub>2.5</sub> exceedance days, whereas

the low group had a higher mean of 14.97 days (20.64; table 2). This increase in exposure was more pronounced in the high and very high groups, with means of 20.29 days (SD 25.48) in the high group and 21.70 days (30.33) in the very high group. The post-hoc Dunn's test identified specific between-group differences (table 3). Statistically significant differences were observed between the very low MDE group and the high MDE group (p=0.025), medium and high groups (p=0.014), very low and very high groups (p=0.0064), and medium and very high groups (p<0.0001; table 3). Median values corroborated the mean trends, indicating that individuals with higher MDE levels typically experience a greater number of exceedance days.

The Kruskal–Wallis analysis also revealed that age-related variations were evident in PM<sub>2.5</sub> exceedance days across MDE groups (H 51.8269; p<0.0001; figure 4B). For the very high MDE group, both adolescents (aged 12–17 years) and young adults (aged 18–25 years) had high mean exceedance days (20.92 [SD 28.81] in adolescents and 22.57 [SD 32.05] in young adults). Adolescents and young adults with medium levels of MDE differed significantly in exposure to PM<sub>2.5</sub> exceedance days from age groups with high (p=0.012) and very high (p<0.0001) MDE levels. Seasonal variations were evident in PM<sub>2.5</sub> exposure across MDE levels (H 152.4771; p<0.0001; figure 4C). The high MDE group in winter had a mean of 35.52 (SD 31.33) PM<sub>2.5</sub> exceedance days, which is higher than any groups with lower MDE levels across all seasons. The high MDE group in winter had about three times as many exceedance days as the very high MDE group in spring (10.85 days [SD 17.21]; p=0.013) and summer (12.94 days [SD 15.80]; p=0.020). The low MDE group in winter had more exceedance days (mean 22.53 days [SD 23.68]) than in the spring (10.34 days [SD 13.62]) and summer (6.86 days [SD 9.31]). MERRA-2 wind direction data showed prevailing winds often



**Figure 3: Relationship between PM<sub>2.5</sub> exceedance days (>15 µg/m<sup>3</sup>) and SVI levels**

(A) Distribution of PM<sub>2.5</sub> exceedance days across SVI levels. (B) Seasonal breakdown of PM<sub>2.5</sub> exceedance days across SVI levels, presented as box plots for each season. SVI=Social Vulnerability Index.

	Mean PM <sub>2.5</sub> exceedance days (SD)	Median PM <sub>2.5</sub> exceedance days (IQR)
<b>Very low SVI</b>		
Autumn	17.00 (15-21)	11.00 (25-75)
Spring	4.00 (5-66)	1.00 (2-00)
Summer	7.50 (6-28)	7.00 (4-25)
Winter	13.12 (12-74)	8.50 (12-75)
<b>Low SVI</b>		
Autumn	16.83 (22-30)	11.00 (9-75)
Spring	3.57 (3-31)	2.00 (3-00)
Summer	7.17 (6-59)	4.00 (9-50)
Winter	14.07 (13-16)	9.00 (17-50)
<b>Medium SVI</b>		
Autumn	28.97 (37-01)	17.00 (20-00)
Spring	16.47 (22-99)	4.00 (16-00)
Summer	12.78 (15-60)	8.00 (11-00)
Winter	30.00 (34-45)	20.00 (26-50)
<b>High SVI</b>		
Autumn	29.35 (45-52)	6.00 (40-00)
Spring	8.87 (9-35)	5.00 (8-00)
Summer	7.47 (9-41)	4.00 (6-00)
Winter	33.54 (33-75)	25.00 (45-00)
<b>Very high SVI</b>		
Autumn	11.95 (10-75)	8.50 (10-25)
Spring	4.80 (4-34)	4.00 (3-50)
Summer	3.33 (2-71)	2.00 (1-00)
Winter	9.55 (9-25)	6.00 (8-00)

SVI=social vulnerability index.

**Table 1: Summary statistics of PM<sub>2.5</sub> exceedance days across SVI groups**

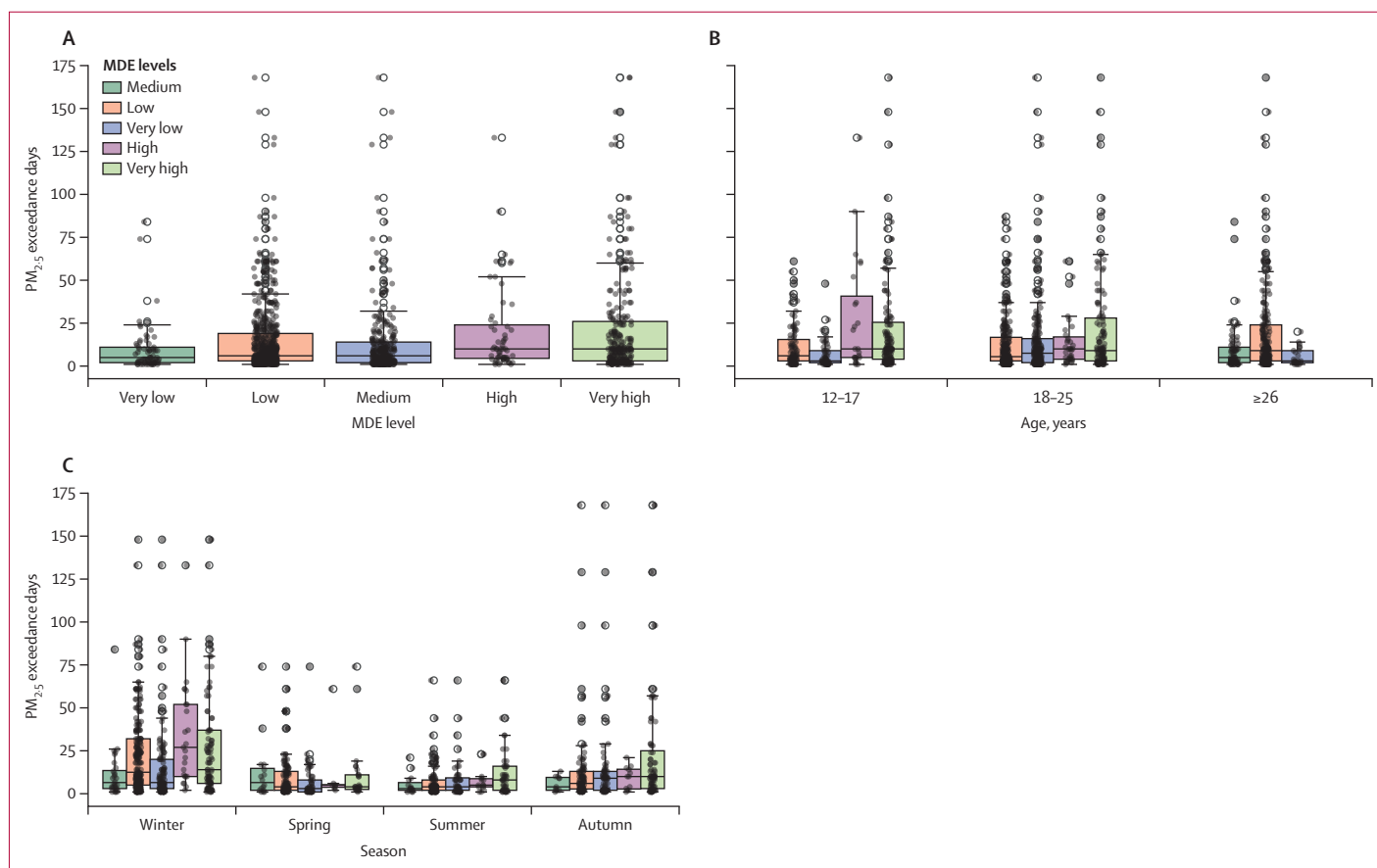
blowing eastward from the lake towards Salt Lake, Duchesne, and surrounding counties.

The two-way ANOVA revealed a highly significant direct (main) effect of PM<sub>2.5</sub> exceedance days on MDE estimates (F 12.341; p=0.0005). The SVI did not show a significant direct effect on MDEs (F 1.282; p=0.26). However, the indirect (interaction) effect between PM<sub>2.5</sub> exceedance days and SVI index was significant (F 6.979; p=0.0084),

indicating that social vulnerability modifies the susceptibility of populations to air quality degradation. The comprehensive analysis examining age groups, seasonality, PM<sub>2.5</sub> exceedance days, and SVI revealed a highly significant direct effect of PM<sub>2.5</sub> exceedance days (F 33.555; p<0.0001), age group (F 425.691; p<0.0001), and seasonality (F 10.181; p<0.0001) on MDE outcomes. The SVI showed a marginal effect (F 4.100; p=0.042).

### Discussion

The analysis of PM<sub>2.5</sub> exceedance days reveals significant negative correlations with both Great Salt Lake area and volume. The correlation with lake volume is notably stronger than with lake area, underscoring the important influence of water volume on local microclimates and atmospheric conditions. Larger water bodies moderate humidity and temperature fluctuations, which directly affect air quality. Seasonal trends reinforce this relationship, with the strongest correlations occurring during winter months, consistent with well documented temperature inversions in the Salt Lake Valley. During these periods, stable atmospheric conditions limit vertical mixing, trapping pollutants near the surface and elevating PM<sub>2.5</sub> concentrations. Additionally, compositional analysis of MERRA-2 PM<sub>2.5</sub> data further clarifies the role of Great Salt Lake desiccation in driving air pollution and health harms. Dust surface mass has increased substantially, contributing around 34% of total PM<sub>2.5</sub>. Sea salt surface mass has also risen, likely due to the drying lakebed and exposed salt crystals. Together, these findings substantiate the role of lake desiccation in air quality degradation, representing a novel and preventable source of air pollution. Meanwhile, sulphate surface mass concentration had a strong downward trend, indicating effective industrial emission controls despite its substantial contribution to PM<sub>2.5</sub>. Organic carbon mass concentration has risen due to biomass burning and wildfires, whereas black carbon mass concentration has decreased slightly, reflecting



**Figure 4:** PM<sub>2.5</sub> exceedance days (>15 µg/m<sup>3</sup>) and MDE prevalence across age and seasons

(A) Distribution of PM<sub>2.5</sub> exceedance days across MDE prevalence levels. (B) PM<sub>2.5</sub> exceedance days stratified by age group and MDE prevalence level. (C) Seasonal variation in PM<sub>2.5</sub> exceedance days across MDE prevalence levels. MDE=major depressive episode.

improvements in diesel engine emissions. These trends show the complex interplay of pollution sources in the region. The elevated PM<sub>2.5</sub> concentrations observed during the 2020s were primarily driven by regional wildfires, highlighting the compounding effects of multiple environmental stressors.

Beyond these atmospheric shifts, the toxicity of PM<sub>2.5</sub> has profound biological implications. In this context, particle size is crucial: the smaller the particle, the greater its potential to induce oxidative stress and inflammation. Once inhaled, these particles can enter the body through multiple pathways—penetrating the nasal epithelium, travelling via the olfactory bulb directly into the brain, or reaching the lungs, where they trigger systemic inflammation through cytokine release.<sup>18</sup> Through these mechanisms, particulate matter can breach physiological barriers and interact with neural tissue, triggering neuroinflammation, disrupting cellular metabolism, and causing oxidative damage to DNA, lipids, and proteins. Although the respiratory and cardiovascular<sup>8–11</sup> effects of such exposure, ranging from asthma to heart disease, are well established, accumulating evidence now implicates chronic particulate exposure in

neurological outcomes,<sup>12–18</sup> including accelerated cognitive decline and increased risk of Alzheimer’s disease and other dementias. The mental health burden associated with air pollution is notable and statistically supported by our analysis. Our findings show statistically significant differences in PM<sub>2.5</sub> exposure across MDE levels in populations surrounding the Great Salt Lake. The pattern suggests that the distribution of individuals with severe depressive symptoms is skewed towards those with higher pollution exposure. The pronounced seasonal variation in the relationship between PM<sub>2.5</sub> exposure and depression, particularly the elevated exceedance days during winter months, suggests a compounding of risk factors. Beyond elevated pollution concentrations, winter-specific factors (eg, reduced sunlight, shorter days, lower physical activity, and reduced social engagement) could further exacerbate depressive symptoms. This seasonal pattern has important implications for public health interventions, suggesting the need for enhanced monitoring and support during high-risk periods.

Future studies should account for these contextual variables to more accurately isolate the effects of air pollution

	MDE count	Mean PM <sub>2.5</sub> exceedance days (SD)	Median PM <sub>2.5</sub> exceedance days (IQR)
Very Low	70	9.73 (14.14)	5 (9)
Low	552	14.97 (20.64)	6 (16)
Medium	296	13.01 (21.88)	6 (12)
High	59	20.29 (25.48)	10 (20)
Very High	247	21.70 (30.33)	10 (23)

MDE=major depressive episode.

**Table 2: Summary statistics of PM<sub>2.5</sub> exceedance days across MDE groups**

	Very Low	Low	Medium	High	Very High
Very Low	..	0.44	1.0	0.025	0.006
Low	0.44	..	0.14	0.42	0.068
Medium	1.0	0.14	..	0.014	0.0001
High	0.025	0.42	0.014	..	1.0
Very High	0.0064	0.068	0.0001	1.0	..

MDE=major depressive episode.

**Table 3: Post-hoc Dunn's test of p values for differences in PM<sub>2.5</sub> exposure (days >15 µg/m<sup>3</sup>) across MDE groups**

on mental health. Our findings showing elevated PM<sub>2.5</sub> exposure in adolescents and young adults with very high MDE levels underscore the need for targeted interventions in these populations. This vulnerability warrants particular attention, as these age groups are at an important developmental phase in which brain maturation and physiological development occur rapidly, rendering them more susceptible to environmental, social, and psychological stressors.

The intersection of environmental exposure and social determinants adds further complexity to understanding mental health outcomes. The relationship between social vulnerability and PM<sub>2.5</sub> exposure revealed unexpected patterns that illuminate the unique nature of this environmental hazard. Although higher SVI groups generally had more PM<sub>2.5</sub> exceedance days, the very high SVI group had lower exposure levels—a finding that reflects Utah's unique geographical distribution of social vulnerability. Counties such as San Juan that have very high SVI scores are located in rural, remote areas far from the Great Salt Lake and major industrial centres, showing that higher social vulnerability does not necessarily correlate with higher pollution exposure in rural settings. This geographical pattern distinguishes lake-derived air pollution from traditional environmental justice concerns, as industrial pollution sources typically concentrate in disadvantaged urban communities. Despite this atypical exposure pattern, social vulnerability remains an important factor in understanding health outcomes. The significant interaction effect between PM<sub>2.5</sub> exceedance days and SVI reveals that social vulnerability acts as an effect modifier, in which the association between pollution and depressive

symptoms steepens as vulnerability increases. For SVI groups with proximal pollution exposure (ie, the medium and high groups), the disparities are driven by familiar systemic issues: the concentration of industrial facilities, transportation corridors, and other pollution sources in low-income and minority neighbourhoods. However, the finding that SVI significantly modifies the PM<sub>2.5</sub>–depression relationship points to complex pathways through which social factors influence susceptibility. This relationship suggests an important distinction: although lake desiccation and resulting air pollution do not appear to directly reflect socioeconomic disparities in exposure (unlike many environmental hazards), social vulnerability still plays a crucial role in determining how individuals respond to pollution exposure. This differential response probably reflects unequal access to exposure buffers, such as high-efficiency air filtration, stable housing, and socio-economic flexibility to limit outdoor exposure during peak pollution events, or protective factors that buffer against environmental susceptibility, such as health care and coping resources. Geographical patterns in exposure provide additional insight into the spatial distribution of risk. Salt Lake County had the highest PM<sub>2.5</sub> exceedance days, reflecting both proximity to the exposed lakebed and high industrial emissions. The downwind positioning of Salt Lake and Duchesne counties relative to prevailing eastward winds from the lake underscores the role of wind-driven dust transport in shaping exposure patterns. This finding has important implications for targeted interventions and highlights the need for regional approaches to air quality management.

Our study has several limitations that should be acknowledged. First, potential exposure measurement errors could arise from assigning county-level air pollution data to county-level major depressive episodes without accounting for an individual's previous exposure to air pollution. Second, extreme weather conditions, such as heatwaves, could contribute to mental health disturbances, potentially confounding the causal relationship between air pollution, climate events, and mental health outcomes. Third, we acknowledge that the exposure threshold identified in this study might not be generalisable to other geographical regions and should be interpreted within its specific environmental and sociodemographic context. Despite these limitations, our findings show a meaningful dose–response relationship: as the frequency and intensity of PM<sub>2.5</sub> exposure days increase, depressive symptoms intensify correspondingly. This association warrants further investigation with more precise exposure measurements and larger effect-size estimates. Large-scale longitudinal studies are particularly needed, with emphasis on vulnerable populations, including young people at crucial developmental stages. To strengthen our understanding of these relationships, future research priorities should include quantitative cohort studies, toxicological

investigations, and biomarker analyses, complemented by qualitative research to elucidate causal mechanisms.

The public health implications of our findings demand urgent attention. Our study highlights the potentially preventable role of desiccated lakebeds to air pollution and depression. Unlike many environmental hazards, this phenomenon does not appear to reflect a direct effect of socioeconomic disparities in exposure patterns, although social vulnerability remains an important modifier of health outcomes. Vulnerable populations often do not have the adaptive capacity to escape environmental stressors, such as occupational requirements for outdoor labour, which likely exacerbates the psychological effect of exposure. The disproportionate burden of PM<sub>2.5</sub> exposure in high-risk areas such as Salt Lake County necessitates targeted interventions focused on seasonal preparedness, especially during winter months when PM<sub>2.5</sub> concentrations typically peak. Addressing the compounded risks of depressive symptoms exacerbated by air pollution necessitates preventive actions and appropriate mental health support, including issuing public health advisories, enhancing air-monitoring systems, and implementing temporary emission reduction measures during periods of high pollution. Strengthening public health literacy is essential to ensure individuals understand the effect of air pollution on mental health more generally. Expanding mental health care for individuals facing multimorbidity is crucial, as coexisting physical and mental health conditions impose an important burden and lead to higher mortality rates. Integrated, cost-effective care models should prioritise community-based interventions that offer both medical and psychological support, alongside prevention and early intervention strategies.

This interdisciplinary investigation of the shrinking Great Salt Lake, air quality, and mental health presents a compelling case for integrating watershed management with efforts that foster sustainable economic growth in the region, while safeguarding community health. By addressing these interconnected issues through targeted interventions, the adverse effects of air pollution on both physical and mental health in affected communities can be mitigated. Ultimately, the insights gained from this research should inform policies related to water management and preventive public health measures, recognising that environmental stewardship and mental health are inextricably linked.

#### Contributors

The contribution of authors is listed according to the CRediT-Taxonomy with the order of authors corresponding to the degree of involvement of the task. MN, KB, and BF conceptualised the study; MN curated the data; MN did the formal analysis; BF acquired the funding; MN did the investigation; MN developed the methods; MN, KB, TC, and BF coordinated the project; BF obtained the resources; MN and KB supervised the study on specific areas of their expertise; MN, BF, and KB accessed and checked the data; and MN visualised the data and wrote the original draft; MN, KB, and BF revised the manuscript. All authors had access to the data and contributed to reviewing, interpreting, and editing the consecutive drafts. All authors

approve the final version and take collective responsibility for all aspects of the work.

#### Declaration of interests

We declare no competing interests.

#### Data sharing

The datasets used in this study are publicly available and can be accessed from <https://www.samhsa.gov/> for data on major depressive episodes, <https://webapps.usgs.gov/gsl/> for data on Great Salt Lake measurements, <https://www.epa.gov/outdoor-air-quality-data/download-daily-data> for data on ground observations of PM<sub>2.5</sub>, <https://gmao.gsfc.nasa.gov/gmao-products/merra-2/> for data on MERRA-2 PM<sub>2.5</sub> components, and <https://www.atsdr.cdc.gov/place-health/php/svi/index.html> for data on the Social Vulnerability Index.

#### Acknowledgments

This research was supported by the US National Aeronautics and Space Administration grant 80MSFC22M0004.

#### References

- Baxter BK, Butler JK. Great Salt Lake biology: a terminal lake in a time of change. Springer, 2020.
- Great Salt Lake Advisory Council. Assessment of potential costs of declining water levels in Great Salt Lake. 2019. <https://utahivers.org/s/Potential-Costs-of-Declining-Water-Levels-in-GSL.pdf> (accessed Jan 20, 2025).
- WHO. WHO global air quality guidelines: particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. 2021. <https://www.who.int/publications/i/item/9789240034228> (accessed Jan 21, 2025).
- Cowley JM, Deering-Rice CE, Lamb JG, et al. Pro-inflammatory effects of inhaled Great Salt Lake Dust particles. *Res Sq* 2024; published online July 24. <https://pmc.ncbi.nlm.nih.gov/articles/PMC11302694/> (preprint)
- National Academies of Sciences, Engineering, and Medicine, Division on Earth and Life Studies, Board on Environmental Studies and Toxicology, Board on Earth Sciences and Resources, Water Science and Technology Board, Owens Lake Scientific Advisory Panel. Effectiveness and impacts of dust control measures for Owens Lake. The National Academies Press, 2020.
- Feizizadeh B, Lakes T, Omarzadeh D, Pourmoradian S. Health effects of shrinking hyper-saline lakes: spatiotemporal modeling of the Lake Urmia drought on the local population, case study of the Shabestar County. *Sci Rep* 2023; **13**: 1622.
- Jones BA, Fleck J. Shrinking lakes, air pollution, and human health: evidence from California's Salton Sea. *Sci Total Environ* 2020; **712**: 136490.
- Burnett R, Chen H, Szyszkwicz M, et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proc Natl Acad Sci USA* 2018; **115**: 9592–97.
- Xing YF, Xu YH, Shi MH, Lian YX. The impact of PM<sub>2.5</sub> on the human respiratory system. *J Thorac Dis* 2016; **8**: e69–74.
- Brunekreef B, Holgate ST. Air pollution and health. *Lancet* 2002; **360**: 1233–42.
- Alexeeff SE, Deosaransingh K, Van Den Eeden S, Schwartz J, Liao NS, Sidney S. Association of long-term exposure to particulate air pollution with cardiovascular events in California. *JAMA Netw Open* 2023; **6**: e230561.
- Wang F, Lian X, Wang Y, et al. Short-term exposure to PM<sub>2.5</sub> and high pollution events on depressive symptoms among adolescents. *J Hazard Mater* 2025; **492**: 138131.
- Bhui K, Newbury JB, Latham RM, et al. Air quality and mental health: evidence, challenges and future directions. *BJPsych Open* 2023; **9**: e120.
- Guo J, Garshick E, Si F, et al. Environmental toxicant exposure and depressive symptoms. *JAMA Netw Open* 2024; **7**: e2420259.
- Bhui K, Ucci M, Kumar P, Jackson SK, Whitby C, Colbeck I, et al. Air quality and mental illness: role of bioaerosols, causal mechanisms and research priorities. *BJPsych Open* 2024; **10**: e149.

- 16 Metcalf JS, Banack SA, Cox PA. Cyanotoxin analysis of air samples from the Great Salt Lake. *Toxins* 2023; **15**: 11659.
- 17 Newell ME, Adhikari S, Halden RU. Systematic and state-of the science review of the role of environmental factors in amyotrophic lateral sclerosis (ALS) or Lou Gehrig's disease. *Sci Total Environ* 2022; **817**: 152504.
- 18 Zundel CG, Ryan P, Brokamp C, et al. Air pollution, depressive and anxiety disorders, and brain effects: A systematic review. *Neurotoxicology* 2022; **93**: 272–300.
- 19 US Geological Survey. Great Salt Lake Reaches New Historic Low. 2021. <https://www.usgs.gov/news/state-news-release/great-salt-lake-reaches-new-historic-low> (accessed Jan 20, 2025).
- 20 Gelaro R, McCarty W, Suárez MJ, et al. The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). *J Clim* 2017; **30**: 5419–54.
- 21 Errico RM, Yang R, Privé NC, et al. Development and validation of observing-system simulation experiments at NASA's Global Modeling and Assimilation Office. *Q J R Meteorol Soc* 2013; **139**: 1162–78.
- 22 US Environmental Protection Agency. National Ambient Air Quality Standards (NAAQS) for PM. 2020. <https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm> (accessed Jan 20, 2025).
- 23 WHO. WHO global air quality guidelines. 2021. <https://www.who.int/news-room/questions-and-answers/item/who-global-air-quality-guidelines> (accessed Jan 20, 2025).
- 24 Geospatial Research, Analysis, and Services Program. Social Vulnerability Index. 2024. <https://www.atsdr.cdc.gov/place-health/php/svi/index.html> (accessed Jan 20, 2025).
- 25 Flanagan BE, Gregory EW, Hallisey EJ, Heitgerd JL, Lewis B. A Social Vulnerability Index for disaster management. *J Homel Secur Emerg Manag* 2011; **8**: 0000102202154773551792.