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Groundwater Lithium Availability Association with Physical and Mental Health Outcomes in United States Populations

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Abstract: Natural consumption of lithium has been linked to a range of beneficial physical and mental health outcomes. We examined the association of regional groundwater lithium concentrations with 12 such outcomes across 47 continental US states and Washington DC in two nationally representative samples from the Behavioral Risk Factor Surveillance System (BRFSS). As drinking groundwater is more likely in rural counties, we performed separate logistic regression analyses in rural and urban populations. Associations between groundwater lithium concentrations and health outcomes were stronger in rural residents and robust to demographics in both rural and urban samples. Compared to regions with lithium concentrations less than 10 μg/L, residents of rural counties with lithium concentrations of 30 μg/L or more exhibited consistently reduced odds of depression diagnosis (adjusted odds ratios [ORs] ranged from 0.64 to 0.88), functional impairment (adjusted ORs ranged from 0.33 to 0.87), and kidney disease diagnosis (adjusted ORs ranged from 0.49 to 0.93); whereas reduced odds of cancer diagnosis were less consistent (adjusted ORs ranged from 0.53 to 1.07). Effect sizes were largest in regions with the highest lithium concentrations. Results in rural populations show a positive correlation (r_s (90) = .79, P <.001) between higher lithium availability and improved health outcomes. More research is needed to determine if optimizing lithium intake may improve physical and mental health.

Keywords: Lithium, Health outcomes, Groundwater, Rural populations

Introduction

Lithium, best known for its use in the treatment of bipolar disorder, is also naturally present at low levels in both food and tap water and is available in the US as a dietary supplement [1-4]. Intriguingly, lithium exposure from natural environmental sources has been linked to a range of beneficial social, psychiatric, and physical health outcomes (e.g., decreased violent crime, drug-related arrests [5, 6], suicide [7, 8], cognitive decline [9-11], cancer [12], and improved heart, bone, and metabolic health [13-15]). While still considered a potentially toxic contaminant by major regulatory organizations [16], lithium's diverse beneficial health effects and known physiologic actions have led some to argue there should be consideration of it as an essential micronutrient [1, 2, 4, 14].

Despite growing evidence of lithium's mental and physical health benefits, epidemiological examination of environmental lithium in a nationally representative US sample is currently lacking. To address this knowledge gap, we assessed the association between median regional groundwater lithium concentrations and mental and physical health outcome data collected from the Behavioral Risk Factor Surveillance System (BRFSS). Given the association between kidney dysfunction and long-term lithium treatment [3, 11], we also evaluated lithium's association with the incidence of kidney disease. Since tap water in rural areas primarily originates from groundwater, while the tap water in most major metropolitan areas comes from comparatively lower-lithium concentration surface waters (eg, lakes, reservoirs and rivers [17-19]), we hypothesized that the mental and physical health benefits of consuming groundwater lithium would be most evident in rural versus urban residents. For added confidence in our results, we analyzed the BRFSS data for 2022 and 2023 independently.

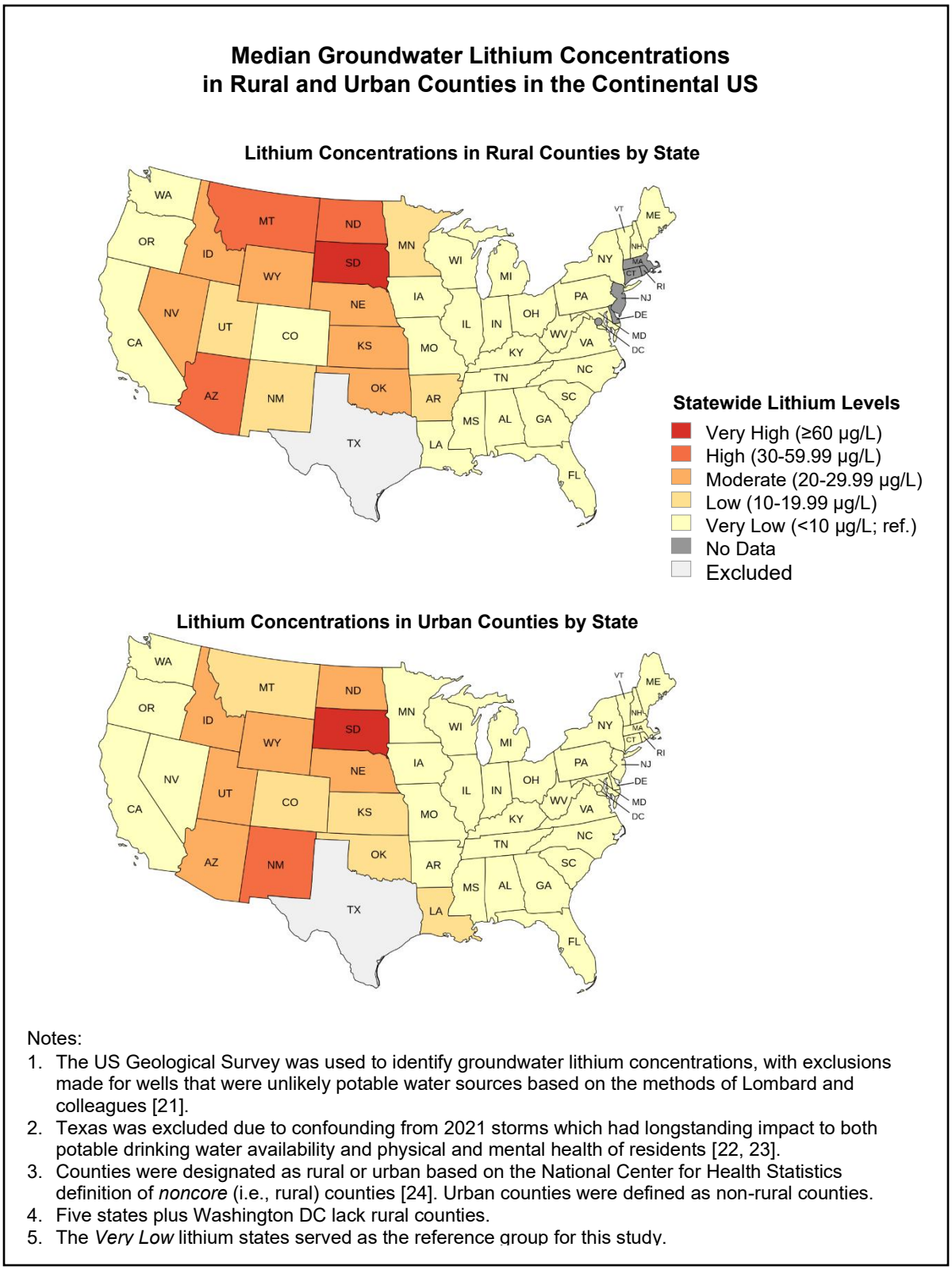
Methods

Respondents: Respondents were drawn from the Center for Disease Control's (CDC) Behavioral Risk Factor Surveillance System (BRFSS) conducted in 2022 and 2023. The BRFSS consists of over 400,000 annual phone interviews with adults nationwide, providing a US representative sample of health-related issues. Methodology is provided on the CDC's website [20]. Precise geographical data, such as county of residence, was unable to be obtained.

Groundwater Lithium Concentrations**:** The US Geological Survey, conducted by the US Department of the Interior, was used to identify groundwater lithium concentrations (measured in μg/L) in wells throughout the continental US and Washington, DC. Wells that were unlikely potable water sources were identified and excluded based on the methods of Lombard and colleagues [21]. Additionally, we excluded Texas over concerns that the longstanding and widespread 2021 power outages left many communities, particularly rural communities, without safe tap water and with limited medical services right before our 2022-2023 study period [22, 23].

As groundwater is more likely to be consumed in rural counties [17-19], we used rural county residence as a proxy variable for lithium consumption. Counties were designated as rural or urban based on the National Center for Health Statistics guidelines [24] definition of *noncore* (i.e., rural) counties. Urban counties were defined as non-rural counties. Statewide medians for rural and urban counties were calculated using regional lithium measurements from the combined USGS samples collected between 2012 and 2025. Regional lithium concentrations were grouped relative to: 1) the EPA's [11] Health Reference Level (HRL) of 10 μg/L, 2) 20 μg/L based on twice the EPA's HRL,

3) 30 µg/L based on the Eurasian Economic Union [25] limit for lithium in drinking water, and 4) 60 µg/L based on higher-level cutoffs from other publications [11, 26]. As shown in Figure 1, this system classified: 1) the rural counties of 29 states and the urban counties of 35 states as *very low* in lithium (below 10 µg/L), 2) the rural counties of 4 states and urban counties from 5 states as *low* in lithium (10-19.99 µg/L), 3) rural and urban areas from 6 states as *moderate* in lithium (20-29.99 µg/L), 4) rural areas from 3 states and urban areas from 1 state as *high* in lithium (30-59.99 µg/L), and 1 state (South Dakota) with both rural and urban counties classified as *very high* in lithium. Note that 5 states plus Washington DC lack rural counties.



Notes:

1. The US Geological Survey was used to identify groundwater lithium concentrations, with exclusions made for wells that were unlikely potable water sources based on the methods of Lombard and colleagues [21].
2. Texas was excluded due to confounding from 2021 storms which had longstanding impact to both potable drinking water availability and physical and mental health of residents [22, 23].
3. Counties were designated as rural or urban based on the National Center for Health Statistics definition of *noncore* (i.e., rural) counties [24]. Urban counties were defined as non-rural counties.
4. Five states plus Washington DC lack rural counties.
5. The *Very Low* lithium states served as the reference group for this study.

Figure 1: Median Groundwater Lithium Concentrations in Rural and Urban Counties in the Continental United States

Outcome Variables: All outcome variables are from 2022 and 2023 BRFSS datasets [27, 28]. Variables were dichotomized to aid in interpretability [29] based on recommended population thresholds and Healthy People 2030 objectives [30].

Depression: Respondents reported whether they have received a depression diagnosis sometime in their lifetime. Reference group: No depression.

Mental Health Days: Respondents reported the quantity of "not good" mental health days within the past 30 days. Reference group: <14 "not good" mental health days [31].

Physical Health Days: Respondents reported the quantity of "not good" physical health days in the past 30 days. Reference group: <14 "not good" physical health days [31].

Activity Limitation Days: Respondents reported how many days during the past 30 days their physical or mental health kept them from maintaining usual activity. Reference group: <14 days with activity limitations [31].

Self-Described Poor Health: Respondents reported their general health using a 5-point Likert scale ranging from 1 (Excellent) to 5 (Poor), which was dichotomized using 'good health' (1-3) as the reference group [31].

Short Sleep: Respondents in 2022 reported their sleep duration in hours during a typical 24-hour period, which was dichotomized at 7 hours. Reference group: 7 or more hours of sleep [30].

Difficulty Concentrating: Respondents reported whether they have serious difficulty concentrating, remembering, or making decisions due to a physical, mental or emotional condition they had at the time of the survey. Reference group: reported, "No."

Difficulty Walking/Stairs: Respondents reported whether they had serious difficulties walking or climbing stairs. Reference group: reported, "No."

Difficulty Getting Dressed/Bathing: Respondents reported whether they had difficulty getting dressed or bathing themselves. Reference group: reported, "No."

Difficulty Performing Errands Alone: Respondents reported whether they had difficulty performing errands such as shopping or visiting the doctor's office due to a physical, mental or emotional condition they had at the time of the survey. Reference group: reported, "No."

Cancer Diagnosis: Respondents reported whether they were ever told they had a "melanoma or any other types of cancer." They were asked directly after a question (not analyzed) about skin cancer that was not a melanoma. Reference group: reported, "No."

Kidney Disease Diagnosis: Respondents reported whether they received a kidney disease diagnosis sometime in their lifetime. Reference group: reported, "No."

Control Variables: The adjusted model controlled for respondent sex, age, race/ethnicity, education, veteran status, marital status, income, obesity, and smoking status.

Analysis: Binomial logistic regressions were conducted using SPSS version 29 (IBM, 2023) using data that was weighted using CDC recommendations [20]. As we used rural county residence as a proxy variable for lithium consumption (described above), analyses were run separately for urban (i.e., non-rural) and rural respondents in both 2022 and 2023 samples. To aid evaluation of lithium as an individual-level intervention, Cohen's *d* was calculated

from Odds Ratio (OR) values, such that OR values of 0.70, 0.40, and 0.23 correspond to Cohen's *d* cut-offs of 0.20, 0.50, and 0.80.

The study protocol was approved by the Walter Reed Army Institute of Research Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects. We conducted the study from February 2025 through July 2026.

Results

Table 1 shows the descriptive statistics for the outcome variables. Table 2 shows the association between groundwater lithium levels and health outcomes for rural residents, and Table 3 shows results for urban residents.

Rural Residents

Rural residents in the states with lithium levels greater than 10 µg/L generally had reduced odds of poor health outcomes relative to residents of very low lithium states (ie, the reference group of states with mean lithium levels below 10 µg/L). For respondent data with independent replications in both analyzed BRFSS sample years (i.e., all health outcomes except for short sleep, for which data were only present in the 2022 BRFSS sample), rural residents of low lithium regions had consistently (i.e., across both the 2022 and 2023 samples) reduced odds of 6 of the 11 poor health outcomes. Rural residents of moderate lithium regions had consistently reduced odds of 9 of the 11; those of high lithium regions had consistently reduced odds of 10 of the 11; while rural residents of very high lithium states had consistently reduced odds of all 11 repeated poor health outcomes. Lastly, rural residents for all lithium levels greater than 10 µg/L had reduced odds of short sleep relative to residents of very low lithium regions, with greater effect for each increase in lithium level.

For rural residents, the magnitude of the effect sizes tended to increase as lithium concentrations increased. Across all 12 outcomes and analyses, rural residents of low lithium regions had a median of 0.95 times the odds (OR range: 0.73 to 1.15) of poor health outcomes relative to very low lithium regions, whereas rural residents of very high lithium regions had a median of 0.57 times the odds of poor health outcomes (OR range: 0.33 to 0.87). To summarize this pattern, we converted to Cohen's d the 92 odds ratios shown in Table 2 and found a high correlation between groundwater lithium levels and effect sizes in rural residents using both the unadjusted (r_s (90) = -.80, P <.001) and adjusted models (r_s (90) = -.79, P <.001).

There was only one occurrence of any of the lithium levels greater than 10 µg/L having consistently higher rates of any negative health outcome, and that was for rural residents of low lithium states having increased odds (OR range: 1.07 to 1.15) of activity limitation days. However, rural residents of higher lithium level states (i.e., moderate to very high) had decreased odds of activity limitation days (OR range: 0.55 - 0.90). In short, higher levels of environmental lithium predicted decreased odds of all 12 poor health outcomes in the rural residents.

Urban Residents

As shown in Table 3, across all 12 outcomes in urban residents, lithium concentrations in groundwater had no overall relationship to outcomes in regions with low (median = 1.00, OR range: 0.89 - 1.23), moderate (median =

0.98, OR range: 0.80 - 1.09) and high (median = 1.06, OR range: 0.85 - 1.34) lithium concentrations. To summarize this pattern, we converted the 69 odds ratios for the regions with low, moderate, and high lithium concentrations shown in Table 3 to Cohen's d. We then correlated these effect sizes with groundwater lithium levels in these urban residents and found no significant correlation using both the unadjusted (r_s (67) = .24, P = .05) and adjusted models (r_s (67) = .15, P = .23).

In contrast, urban residents living in the very high lithium state of South Dakata had reduced odds of 6 of 12 poor health outcomes (median OR = 0.87, OR range: 0.60 to 1.36). Specifically, they had consistently decreased odds for physical health days, activity limitation days, self-rated poor health, difficulty walking, and kidney disease diagnosis. Additionally, like rural residents, urban residents of the low to very high lithium levels had reduced odds of short sleep relative to residents of the very low lithium regions, with greater effect for each increase in lithium level (2022 sample).

Discussion

In our nationally representative samples of rural and urban residents, the rural residents of states with higher median groundwater lithium levels reported significantly less mental health issues, less physical health issues, and less functional impairment than rural residents of states with very low groundwater lithium levels. These results for rural residents remained robust even when adjusting for demographics, smoking, and obesity. Furthermore, results from both the 2022 and 2023 nationally representative samples were suggestive of a potential dose-response curve in which the magnitude of effect sizes increased as groundwater lithium concentrations increased. This supports our hypothesis that rural residents in states with higher groundwater lithium concentrations would have better physical and mental health outcomes when compared to rural residents in states with lower groundwater lithium levels.

Also, as we hypothesized, results were less robust in residents of urban counties. In urban residents, only the residents of the state with very high groundwater lithium concentrations exhibited consistently decreased odds of at least half of the poor health outcomes we studied; effect sizes were lower than in the rural population within the state. We attribute these results to the decreased reliance of urban areas on local groundwater for drinking water, as groundwater generally has higher lithium levels than other water sources [17, 18].

Public Health Implications

The current findings showing a correlation between lithium exposure and reduced risk of a broad range of health outcomes support the idea that lithium plays a systemic role in health and may be a necessary micronutrient [1, 2, 4, 14]. Even though naturally occurring lithium levels in US drinking water sources are orders of magnitude lower than those currently prescribed for psychiatric disorders, the effect sizes observed in rural populations suggest the potential for trace lithium to produce meaningful health improvements at individual and population levels [32]. As lithium appears protective against the 12 health factors we studied, might it also positively impact other outcomes, to include life expectancy? With further studies to include randomized, controlled trials, we could learn more definitively if microdosed lithium through supplementation could be a viable preventative strategy against

maladies such as depression, cancer, kidney disease, cognitive impairment including dementia, and complications of these to include sick days, difficulty with activities of daily living, and early death. Thus, lithium supplementation in food or water, or as an individually dosed supplement, should be considered from health and economic perspectives.

Unlike previous research on health risks of lithium overexposure, the current study highlights potential health benefits of naturally occurring trace levels of lithium from the environment. In contrast to the well-known association between chronic high-dose lithium psychiatric treatment and kidney disfunction [11], our results, as far as we can determine, are the first to indicate that exposure to trace environmental lithium may be protective against kidney disease in humans. This finding aligns with recent research suggesting beneficial effects of environmental lithium on mortality in kidney transplant patients [33]. Additionally, as far as we can determine, the present study is only the second human study to indicate that trace lithium in drinking water may be protective against cancer [12].

Limitations

We used rural residence as a proxy for lithium consumption from groundwater, and this novel methodology allowed us to accurately predict which regions had reduced odds of poor health outcomes. Our methodology and all previous lithium availability-based methodologies assume that residents consume tap water. However, a 2017-2018 national survey found that over half of adults reported they did not drink any tap water on a given day, and over one-third reported they exclusively drink bottled water [34]. Studies have also demonstrated that tap water avoidance is correlated with food insecurity [35], which is more prevalent in rural populations [36], and with minority groups that are more common in urban populations [37]. This draws attention to the fact that a significant portion of BRFSS respondents were likely not consuming tap water; hence, the current study likely underestimated the magnitude of lithium's beneficial health effects.

While this study offers important contributions, several other limitations must be noted. First, although the study replicated findings across nationally representative samples, the observational nature of the study precludes conclusions of causation. Second, despite the current study controlling for demographics, obesity, and smoking, future research may find it useful to examine additional covariates and the potential moderating influences of these variables (e.g., age, veteran status, and body mass index) on the health impact of lithium consumption. Third, notwithstanding the study's potential utility for policymakers, defining regions based on urbanization-levels within a state, instead of more localized data, likely further underestimated the effect of lithium and could have influenced the risk of ecological bias. Fourth, although we included 47 US states and Washington DC, we excluded Texas because of a natural disaster that occurred directly before our study period, and this exclusion may have impacted some of the results. Fifth, our classification of regions was based on health referent levels for lithium proposed by US and Eurasian government agencies [16, 25, 26], but research would be improved by developing dose-response curves for lithium. Lastly, although the samples used were from CDC's leading surveillance system, the present study relied on self-reported health outcomes. Thus, future studies could benefit from incorporating more objective health measures, such as clinical assessments and biomarkers, along with improved measures of lithium intake.

Conclusion

This study contributes to the growing body of literature on benefits of low dose lithium by utilizing geographic patterns in groundwater lithium concentrations and their associations with diverse health outcomes in nationally representative US samples. The findings suggest that lithium may have the potential to help prevent functional impairment, mental health conditions, cancer, kidney disease, and increase well-being and productivity. With decreased rates of these maladies, life expectancy may potentially be increased. Given the personal and financial costs of these health conditions, even modest improvements in population-level health could translate to significant societal and economic benefits. Therefore, further study is needed on the potentially essential nature and optimal levels of lithium.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Stephen Krauss, Andrew Borrell, and Alyssa Soumoff contributed to the study conception and design. Stephen Krauss, Andrew Borrell, Kamara Adogu, Marissa Bolouri-rad, Kristian Krslovic, and Tion Hines performed data analysis. The manuscript was written primarily by Stephen Krauss, Andrew Borrell, and Alyssa Soumoff; and all authors commented on versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The study relied exclusively on publicly available data available from the CDC and Department of the Interior and is available at https://www.cdc.gov/brfss/index.html and https://www.usgs.gov/ respectively.

Ethics Approval

The study protocol was approved by the Walter Reed Army Institute of Research Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects.

Consent to Participate

The participants consented as part of their participation with the BRFSS and with knowledge that their deidentified data would be made available for further study.

Consent to Publish

Not applicable. The manuscript does not contain any individual person's data.

Disclaimers

The views expressed in this manuscript reflect the results of research conducted by the authors and do not necessarily reflect the official policy or position of the Defense Health Agency, Department of War, nor the U.S. Government. No endorsement of any non-federal entity, dietary supplement, commercial product, service, or activity is approved or implied by this publication.

References

1. Cherpakov RA, Grebenchikov OA, Makarova AM, Antonova VV, Boeva EA (2026) Manifestations of Lithium Deficiency in the Human Body: What is Known to Date (A Narrative Review). Biol Trace Elem Res, 10.1007/s12011-026-05325-w. Advance online publication. https://doi.org/10.1007/s12011-026-05325-w
2. Marshall TM (2015) Lithium as a nutrient. J Am Phys Surg 20:104-109.
3. Pacholko AG, Bekar LK (2021) Lithium orotate: a superior option for lithium therapy? Brain Behav 11(8):e2262. https://doi.org/10.1002/brb3.2262
4. Szklarska D, Rzymski P (2018) Is lithium a micronutrient? From biological activity and epidemiological observation to food fortification. Biol Trace Elem Res 189(1):18-27. https://doi.org/10.1007/s12011-018-1455-2
5. Giotakos O, Tsouvelas G, Nisianakis P, Giakalou V, Lavdas A, Tsiamitas C, Panagiotis K, Kontaxakis V (2015) A negative association between lithium in drinking water and the incidences of homicides, in Greece. Biol Trace Elem Res 164(2):165-168. https://doi.org/10.1007/s12011-014-0210-6
6. Schrauzer GN, Shrestha KP (1990) Lithium in drinking water and the incidences of crimes, suicides, and arrests related to drug addictions. Biol Trace Elem Res 25(2):105-113. https://doi.org/10.1007/bf02990271
7. Eyre-Watt B, Mahendran E, Suetani S, Firth J, Kisely S, Siskind D (2020) The association between lithium in drinking water and neuropsychiatric outcomes: a systematic review and meta-analysis from across 2678 regions containing 113 million people. Aust N Z J Psychiatry 55(2):139-152. https://doi.org/10.1177/0004867420963740
8. Harandi H, Ahmadinia H, Ghaffarian-Bahraman A, Alimoradi H, Nasab ZB, Rezaeian M (2024) Correlation between lithium concentrations in drinking water and suicide attempt in the southeast of Iran. Environ Monitoring Assess 196(11):1108. https://doi.org/10.1007/s10661-024-13325-3
9. Aron L, Ngian ZK, Qiu C, Choi J, Liang M, Drake DM, Hamplova SE, Lacey EK, Roche P, Yuan M, Hazaveh SS, Lee EA, Bennett DA, Yankner BA (2025) Lithium deficiency and the onset of Alzheimer's disease. Nature 645,712-721, https://doi.org/10.1038/s41586-025-09335-x
10. Kessing LV, Gerds TA, Knudsen NN, Jørgensen LF, Kristiansen SM, Voutchkova D, Ernstsen V, Schullehner J, Hansen B, Andersen PK, Ersbøll AK (2017) Association of lithium in drinking water with the incidence of dementia. JAMA Psychiatry 74(10):1005-1011. https://doi.org/10.1001/jamapsychiatry.2017.2362
11. Wen J, Sawmiller D, Wheeldon B, Tan J (2019) A review for lithium: pharmacokinetics, drug design, and toxicity. CNS Neurol Disord Drug Targets 18(10):769-778. https://doi.org/10.2174/1871527318666191114095249

12. Luo J, Zheng L, Jin Z, Yang Y, Krakowka WI, Hong E, Lombard M, Ayotte J, Ahsan H, Pinto JM, Aschebrook-Kilfoy B (2025) Cancer risk and estimated lithium exposure in drinking groundwater in the US. JAMA Netw Open 8(2):e2460854. https://doi.org/10.1001/jamanetworkopen.2024.60854
13. Barkins R (2016) Low-dose lithium and its health supporting effects. Nutritional Perspectives: Journal of the Council on Nutrition. 39(3):32-34.
14. Hamstra SI, Roy BD, Tiidus P, MacNeil AJ, Klentrou P, MacPherson RE, Fajardo VA (2022) Beyond its psychiatric use: the benefits of low-dose lithium supplementation. Curr Neuropharmacol 21(4):891-910. https://doi.org/10.2174/1570159x20666220302151224
15. Kumar P, Gupta R, Yadav M, Patel R, Meena MK, Gupta A (2026) Association of Serum Lithium Levels with Insulin Resistance in Type-2 Diabetes Patients. Biol Trace Elem Res 204,7501-7510 https://doi.org/10.1007/s12011-026-05203-5
16. US Environmental Protection Agency (2023) Technical Summary: Lithium in Drinking Water, a Resource for Primacy Agencies. https://nepis.epa.gov/Exe/ZyPDF.cgi/P1018SI8.PDF?Dockey=P1018SI8.PDF. Accessed 24 March 2026.
17. Sharma N, Westerhoff P, Zeng C (2022) Lithium occurrence in drinking water sources of the United States. Chemosphere 305:135458. https://doi.org/10.1016/j.chemosphere.2022.135458
18. Sharp JM Jr. (1997) Ground-water supply issues in urban and urbanizing areas. In: Chilton J, ed. Groundwater in the Urban Environment: Volume 1: Problems, Processes and Management. AA Balkema, pp 67-74.
19. US Department of the Interior (2024) How important is groundwater? https://www.usgs.gov/faqs/how-important-groundwater. Accessed 24 June 2025.
20. Centers for Disease Control and Prevention (2023) The Behavioral Risk Factor Surveillance System (BRFSS) Complex Sampling Weights and Preparing 2022 BRFSS Module Data for Analysis. https://www.cdc.gov/brfss/annual_data/2022/pdf/Complex-Sampling-Weights-and-Preparing-Module-Data-for-Analysis-2022-508.pdf Accessed 7 July 2026.
21. Lombard MA, Brown EE, Saftner DM, Arienzo MM, Fuller-Thomson E, Brown CJ, Ayotte JD (2024) Estimating lithium concentrations in groundwater used as drinking water for the conterminous United States. Environ Sci Technol 58(2):1255-1264. https://doi.org/10.1021/acs.est.3c06118
22. Flores NM, McBrien H, Do V, Kiang MV, Schlegelmilch J, Casey JA (2023) The 2021 Texas power crisis: distribution, duration, and disparities. J Expo Sci Environ Epidemiol 33(1):21-31. https://doi.org/10.1038/s41370-022-00462-5
23. Sugg MM, Wertis L, Ryan SC, Green S, Singh D, Runkle JD (2023) Cascading disasters and mental health: the February 2021 winter storm and power crisis in Texas, USA. Sci Total Environ 880:163231. https://doi.org/10.1016/j.scitotenv.2023.163231
24. Ingram DD, Franco SJ (2014) 2013 NCHS urban-rural classification scheme for counties. Vital Health Stat 2. (166):1-73.

25. Eurasian Economic Union (2017) EAEU Technical Regulation on Safety of Packaged Potable Water Including Natural Mineral Water (TR EAEU 044/2017). Translated by the US Dept of Agriculture, Foreign Agricultural Service, Global Agricultural Information Network. Report Number RS1752.
26. Lindsey BD, Belitz K, Cravotta III CA, Toccalino PL, Dubrovsky NM (2021) Lithium in groundwater used for drinking-water supply in the United States. Sci Total Environ 767:144691. https://doi.org/10.1016/j.scitotenv.2020.144691
27. National Center for Chronic Disease Prevention and Health Promotion (US), Division of Population Health, Population Health Surveillance Branch (2022) Behavioral Risk Factor Surveillance System: LLCP 2022 Codebook Report: Overall Version Data Weighted With _LLCPWT. CDC. https://www.cdc.gov/brfss/annual_data/annual_2022.html. Accessed 21 April 2025.
28. National Center for Chronic Disease Prevention and Health Promotion (US), Division of Population Health, Population Health Surveillance Branch (2023) Behavioral Risk Factor Surveillance System: LLCP 2022 Codebook Report: Overall Version Data Weighted With _LLCPWT. CDC. https://www.cdc.gov/brfss/annual_data/annual_2023.html. Accessed 21 April 2025.
29. Nelson SP, Ramakrishnan V, Nietert PJ, Kamen DL, Ramos PS, Wolf BJ (2017) An evaluation of common methods for dichotomization of continuous variables to discriminate disease status. Commun Stat Theory Methods 46(21):10823-10834. https://doi.org/10.1080/03610926.2016.1248783
30. Centers for Disease Control and Prevention. Healthy People 2030 Objectives. https://odphp.health.gov/healthypeople/objectives-and-data/find-objectives. Accessed 30 June 2026.
31. Moriarty DG, Zack MM, Kobau R (2003) The Centers for Disease Control and Prevention's Healthy Days Measures – Population tracking of perceived physical and mental health over time. Health Qual Life Outcomes 1:37. https://doi.org/10.1186/1477-7525-1-37
32. Carey EG, Ridler I, Ford TJ, Stringaris A (2023) Editorial perspective: when is a 'small effect' actually large and impactful? J Child Psychol Psychiatry 64(11):1643-1647. https://doi.org/10.1111/jcpp.13840
33. Post A, Kremer D, Groothof D, Seidel U, Huebbe P, Franssen CF, Kema IP, Lüersen K, Rimbach G, Bakker SJ (2023) Dietary lithium intake, graft failure and mortality in kidney transplant recipients. Nephrol Dial Transplant 38(8):1867-1879. https://doi.org/10.1093/ndt/gfad012
34. Rosinger AY (2022) Using water intake dietary recall data to provide a window into US water insecurity. J Nutr 152(5):1263-1273. https://doi.org/10.1093/jn/nxac036
35. Rosinger AY (2023) Water needs, water insecurity, and human biology. Annu Rev Anthropol 52(1):93-113. https://doi.org/10.1146/annurev-anthro-052621-024346
36. Byker Shanks C, Andress L, Hardison-Moody A, Jilcott Pitts S, Patton-Lopez M, Prewitt TE, Dupuis V, Wong K, Kirk-Epstein M, Engelhard E, Hake M (2022) Food insecurity in the rural United States: an examination of struggles and coping mechanisms to feed a family among households with a low-income. Nutrients 14(24):5250. https://doi.org/10.3390/nu14245250
37. Colburn AT, Kavouras SA (2021) Tap water consumption and perceptions in United States Latinx adults. Nutrients 13(9):2999. https://doi.org/10.3390/nu13092999

406 Table 1: Descriptive statistics of outcome variables by rural and urban subsamples.

	2022	2023
Outcomes	**% Positive**	**% Positive**
Rural Residents	n = 52,069	n = 55,280
Depression Diagnosis	21.80%	21.90%
Poor Mental Health Days (14+/month)	15.93%	16.62%
Poor Physical Health Days (14+/month)	15.98%	16.43%
Activity Limitation Days (14+/month)	20.77%	20.70%
Self-Rated Poor Health	22.37%	24.24%
Short Sleep	36.09%	-
Difficulty Concentrating	15.45%	15.29%
Difficulty Dressing	4.99%	5.17%
Difficulty Walking	18.90%	18.56%
Difficulty Performing Errands Alone	9.63%	10.54%
Cancer Diagnosis	9.35%	9.92%
Kidney Diagnosis	4.20%	4.26%
Urban Residents	n = 355,900	n = 359,661
Depression Diagnosis	20.73%	20.15%
Poor Mental Health Days (14+/month)	15.71%	15.43%
Poor Physical Health Days (14+/month)	12.50%	12.64%
Activity Limitation Days (14+/month)	16.60%	16.77%
Self-Rated Poor Health	17.36%	18.57%
Short Sleep	35.95%	-
Difficulty Concentrating	13.24%	13.39%
Difficulty Dressing	3.73%	3.70%
Difficulty Walking	13.34%	13.19%
Difficulty Performing Errands Alone	7.84%	7.73%
Cancer Diagnosis	8.22%	8.06%
Kidney Diagnosis	3.69%	3.83%

407 Notes: Data were sourced from the Center for Disease Control's (CDC) Behavioral Risk Factor Surveillance System
408 (BRFSS) conducted in 2022 and 2023 [27, 28]. The above data represents responses from the continental United
409 States with the exception of Texas. Means and percentages were weighted to be nationally representative.
410

411 Table 2: Unadjusted and adjusted effects of groundwater lithium concentrations on health outcomes in rural
412 residents.

Outcome	Groundwater Lithium[2]	Unadjusted Odds Ratio (95% CI)		Adjusted[1] Odds Ratio (95% CI)	
		2022	2023	2022	2023
Depression Diagnosis[3]	Low	1.01 (1.01-1.02)	0.92 (0.91-0.92)	1.01 (1.01-1.02)	0.93 (0.92-0.93)
	Moderate	0.83 (0.83-0.84)	0.82 (0.81-0.82)	0.82 (0.82-0.83)	0.83 (0.83-0.84)
	High	0.87 (0.86-0.87)	0.81 (0.81-0.82)	0.88 (0.87-0.88)	0.84 (0.83-0.84)
	Very High	0.75 (0.74-0.76)	0.70 (0.69-0.71)	0.71 (0.70-0.72)	0.64 (0.63-0.65)^{S}
Mental Health Days[4]	Low	0.97 (0.96-0.98)	0.94 (0.94-0.95)	0.98 (0.98-0.99)	0.95 (0.95-0.96)
	Moderate	0.87 (0.86-0.87)	0.84 (0.84-0.85)	0.87 (0.86-0.87)	0.87 (0.86-0.87)
	High	0.82 (0.81-0.83)	0.78 (0.77-0.79)	0.80 (0.79-0.81)	0.78 (0.77-0.79)
	Very High	0.62 (0.61-0.63)^{S}	0.70 (0.69-0.71)	0.55 (0.54-0.56)^{S}	0.59 (0.58-0.6)^{S}
Physical Health Days[4]	Low	0.99 (0.99-1.00)	0.92 (0.92-0.93)	1.03 (1.02-1.03)	0.94 (0.93-0.94)
	Moderate	0.82 (0.81-0.82)	0.85 (0.84-0.85)	0.84 (0.84-0.85)	0.88 (0.87-0.88)
	High	0.76 (0.75-0.77)	0.81 (0.81-0.82)	0.80 (0.79-0.8)	0.83 (0.82-0.83)
	Very High	0.41 (0.4-0.41)^{S}	0.51 (0.5-0.52)^{S}	0.35 (0.35-0.36)^{M}	0.49 (0.48-0.5) ^{S}
Activity Limitation Days[4]	Low	1.07 (1.06-1.07)	1.10 (1.10-1.11)	1.08 (1.08-1.09)	1.15 (1.14-1.15)
	Moderate	0.82 (0.81-0.82)	0.84 (0.83-0.84)	0.82 (0.82-0.83)	0.90 (0.89-0.91)
	High	0.75 (0.74-0.75)	0.78 (0.77-0.78)	0.75 (0.74-0.76)	0.80 (0.79-0.81)
	Very High	0.64 (0.62-0.65)^{S}	0.62 (0.61-0.63)^{S}	0.55 (0.54-0.57)^{S}	0.61 (0.59-0.62)^{S}
Self-Rated Poor Health[5]	Low	0.85 (0.84-0.85)	0.91 (0.91-0.92)	0.87 (0.86-0.87)	0.95 (0.94-0.95)
	Moderate	0.84 (0.83-0.84)	0.80 (0.79-0.80)	0.89 (0.88-0.89)	0.86 (0.86-0.87)
	High	0.74 (0.73-0.75)	0.77 (0.76-0.77)	0.80 (0.79-0.81)	0.85 (0.84-0.85)
	Very High	0.61 (0.6-0.62)^{S}	0.84 (0.83-0.85)	0.53 (0.53-0.54)^{S}	0.86 (0.85-0.88)
Short Sleep[6]	Low	0.86 (0.86-0.87)	-	0.86 (0.86-0.87)	-
	Moderate	0.84 (0.84-0.85)	-	0.84 (0.84-0.85)	-
	High	0.80 (0.80-0.81)	-	0.80 (0.79-0.80)	-
	Very High	0.60 (0.59-0.61)^{S}	-	0.56 (0.55-0.57)^{S}	-
Difficulty Concentrating[3]	Low	0.95 (0.95-0.96)	0.97 (0.96-0.97)	0.96 (0.95-0.96)	0.97 (0.97-0.98)
	Moderate	0.88 (0.88-0.89)	0.96 (0.95-0.96)	0.89 (0.88-0.89)	1.02 (1.02-1.03)
	High	0.69 (0.69-0.70)^{S}	0.79 (0.78-0.8)	0.69 (0.68-0.70)^{S}	0.82 (0.82-0.83)
	Very High	0.38 (0.37-0.39)^{M}	0.77 (0.76-0.78)^{S}	0.33 (0.32-0.34)^{M}	0.68 (0.67-0.69)^{S}
Difficulty Dressing[3]	Low	0.99 (0.98-1.00)	0.73 (0.72-0.73)	1.03 (1.02-1.04)	0.75 (0.75-0.76)
	Moderate	0.87 (0.86-0.88)	0.74 (0.74-0.75)	0.91 (0.9-0.92)	0.85 (0.84-0.86)
	High	0.67 (0.66-0.68)^{S}	0.76 (0.75-0.77)	0.71 (0.69-0.72)	0.87 (0.85-0.88)
	Very High	0.66 (0.64-0.68)^{S}	0.49 (0.48-0.51)^{S}	0.55 (0.54-0.57)^{S}	0.56 (0.54-0.58)^{S}
Difficulty Walking[3]	Low	0.91 (0.91-0.92)	0.84 (0.83-0.84)	0.94 (0.94-0.95)	0.88 (0.88-0.89)
	Moderate	0.90 (0.89-0.9)	0.91 (0.9-0.91)	0.94 (0.94-0.95)	1.03 (1.03-1.04)
	High	0.66 (0.66-0.67)^{S}	0.70 (0.69-0.71)^{S}	0.68 (0.68-0.69)^{S}	0.76 (0.76-0.77)
	Very High	0.53 (0.52-0.54)^{S}	0.76 (0.75-0.77)	0.42 (0.41-0.43)^{S}	0.86 (0.85-0.88)
Difficulty Running Errands[3]	Low	0.95 (0.95-0.96)	0.86 (0.85-0.87)	0.97 (0.97-0.98)	0.88 (0.88-0.89)
	Moderate	0.94 (0.93-0.94)	0.83 (0.83-0.84)	0.98 (0.97-0.99)	0.91 (0.9-0.91)
	High	0.66 (0.65-0.67)^{S}	0.72 (0.72-0.73)	0.69 (0.68-0.70)^{S}	0.77 (0.76-0.78)
	Very High	0.45 (0.44-0.47)^{S}	0.49 (0.48-0.50)^{S}	0.40 (0.39-0.41)^{M}	0.45 (0.44-0.46)^{S}
Cancer Diagnosis[3]	Low	0.98 (0.97-0.99)	0.92 (0.92-0.93)	0.99 (0.98-0.99)	0.95 (0.94-0.96)
	Moderate	0.90 (0.89-0.90)	0.97 (0.96-0.98)	0.87 (0.86-0.87)	0.97 (0.96-0.97)
	High	0.86 (0.85-0.87)	1.07 (1.06-1.08)	0.79 (0.78-0.80)	1.04 (1.03-1.05)
	Very High	0.62 (0.6-0.63)^{S}	0.53 (0.52-0.55)^{S}	0.53 (0.52-0.54)^{S}	0.57 (0.56-0.58)^{S}
Kidney Disease Diagnosis[3]	Low	0.80 (0.79-0.81)	0.99 (0.98-1)	0.82 (0.81-0.83)	1.03 (1.02-1.04)
	Moderate	0.93 (0.92-0.93)	0.92 (0.91-0.93)	0.97 (0.96-0.98)	0.98 (0.97-0.98)
	High	0.81 (0.8-0.82)	0.93 (0.92-0.95)	0.87 (0.85-0.88)	0.93 (0.91-0.94)
	Very High	0.51 (0.49-0.53)^{S}	0.80 (0.78-0.82)	0.49 (0.47-0.51)^{S}	0.87 (0.85-0.9)

Notes: Grey-shaded cells denote OR 95% CI overlaps 1.00 (i.e., not significant); Green-shaded cells denote Cohen's d $0.20 \leq d < .50$ or $0.50 \leq d < 0.80$ (superscript S and M, respectively).

[1]The adjusted binomial logistic regression model controlled for sex, age, race/ethnicity, education, veteran status, marital status, income, obesity, and smoking status.
[2]Low, Moderate, High, and Very High Lithium = 10-19.99, 20-29.99, 30-59.99, ≥60 µg/L, respectively; reference group: <10 µg/L (Very Low). The US Geological Survey was used to identify groundwater lithium concentrations, with exclusions made for wells that were unlikely potable water sources based on the methods of Lombard and colleagues [21].
[3]Reference group response "No."
[4]Reference group response <14 days.
[5]Reference group Likert Scale response ≤ 3.
[6]Reference group response ≥ 7 hours of sleep.

413

414 Table 3: Unadjusted and adjusted effects of groundwater lithium concentrations on health outcomes in urban
415 residents.

Outcome	Groundwater Lithium[2]	Unadjusted Odds Ratio (95% CI)		Adjusted[1] Odds Ratio (95% CI)	
		2022	2023	2022	2023
Depression Diagnosis[3]	Low	1.19 (1.19-1.20)	1.23 (1.23-1.23)	1.15 (1.14-1.15)	1.16 (1.16-1.17)
	Moderate	1.07 (1.06-1.07)	1.04 (1.04-1.04)	1.03 (1.03-1.03)	1.00 (1.00-1.01)
	High	1.01 (1.01-1.02)	1.2 0(1.19-1.2)	1.05 (1.05-1.06)	1.29 (1.29-1.3)
	Very High	0.85 (0.84-0.86)	1.35 (1.34-1.36)	0.74 (0.73-0.74)	1.12 (1.11-1.13)
Mental Health Days[4]	Low	1.12 (1.12-1.12)	1.12 (1.11-1.12)	1.08 (1.08-1.08)	1.06 (1.06-1.06)
	Moderate	1.02 (1.02-1.02)	0.95 (0.95-0.96)	1.01 (1.00-1.01)	0.95 (0.95-0.95)
	High	1.06 (1.05-1.06)	1.04 (1.04-1.05)	1.03 (1.02-1.03)	1.03 (1.02-1.03)
	Very High	0.89 (0.89-0.9)	0.99 (0.99-1.00)	0.83 (0.82-0.84)	0.87 (0.87-0.88)
Physical Health Days[4]	Low	1.00 (0.99-1.00)	1.01 (1.01-1.01)	0.99 (0.99-0.99)	1.00 (1.00-1.01)
	Moderate	1.00 (0.99-1.00)	0.92 (0.91-0.92)	1.02 (1.02-1.03)	0.93 (0.93-0.94)
	High	1.18 (1.17-1.18)	1.09 (1.08-1.1)	1.08 (1.08-1.09)	0.99 (0.98-0.99)
	Very High	0.80 (0.79-0.81)	0.85 (0.84-0.85)	0.79 (0.78-0.8)	0.79 (0.78-0.8)
Activity Limitation Days[4]	Low	1.00 (0.99-1.00)	1 .00(1.00-1.00)	0.98 (0.98-0.98)	0.98 (0.98-0.99)
	Moderate	0.96 (0.96-0.97)	0.92 (0.92-0.92)	0.99 (0.99-0.99)	0.95 (0.94-0.95)
	High	1.34 (1.33-1.34)	1.23 (1.23-1.24)	1.22 (1.21-1.23)	1.15 (1.14-1.16)
	Very High	0.65 (0.64-0.65)[S]	0.87 (0.86-0.88)	0.62 (0.61-0.62)[S]	0.82 (0.81-0.83)
Self-Rated Poor Health[5]	Low	0.97 (0.97-0.98)	0.98 (0.98-0.98)	0.98 (0.98-0.99)	0.99 (0.98-0.99)
	Moderate	0.94 (0.94-0.95)	0.90 (0.90-0.90)	0.99 (0.99-0.99)	0.94 (0.94-0.94)
	High	1.22 (1.21-1.22)	1.26 (1.26-1.27)	1.00 (1.00-1.01)	1.05 (1.05-1.06)
	Very High	0.83 (0.83-0.84)	0.87 (0.86-0.87)	0.88 (0.87-0.89)	0.89 (0.89-0.9)
Short Sleep[6]	Low	0.94 (0.94-0.94)	-	0.93 (0.93-0.93)	-
	Moderate	0.92 (0.92-0.92)	-	0.95 (0.95-0.95)	-
	High	0.88 (0.88-0.88)	-	0.85 (0.85-0.85)	-
	Very High	0.77 (0.76-0.77)	-	0.80 (0.79-0.80)	-
Difficulty Concentrating[3]	Low	1.18 (1.18-1.18)	1.20 (1.2-1.2)	1.14 (1.14-1.15)	1.16 (1.16-1.16)
	Moderate	1.06 (1.06-1.06)	1.02 (1.02-1.02)	1.05 (1.05-1.05)	1.01 (1.01-1.01)
	High	1.17 (1.16-1.17)	1.12 (1.12-1.13)	1.03 (1.03-1.04)	1.03 (1.03-1.04)
	Very High	0.78 (0.78-0.79)	1.18 (1.17-1.19)	0.74 (0.73-0.74)	1.06 (1.05-1.07)
Difficulty Dressing[3]	Low	0.98 (0.97-0.98)	1.04 (1.04-1.04)	0.98 (0.98-0.98)	1.05 (1.04-1.05)
	Moderate	0.85 (0.85-0.86)	0.80 (0.79-0.8)	0.95 (0.94-0.95)	0.88 (0.88-0.89)
	High	1.10 (1.09-1.1)	1.18 (1.17-1.19)	0.98 (0.97-0.99)	1.06 (1.06-1.07)
	Very High	0.95 (0.94-0.97)	1.26 (1.24-1.28)	1.03 (1.02-1.05)	1.36 (1.34-1.38)
Difficulty Walking[3]	Low	1.02 (1.02-1.02)	1.05 (1.05-1.05)	1.05 (1.05-1.05)	1.08 (1.08-1.08)
	Moderate	0.92 (0.91-0.92)	0.91 (0.91-0.91)	1.00 (1.00-1.01)	0.99 (0.99-0.99)
	High	1.13 (1.12-1.13)	1.08 (1.07-1.08)	1.06 (1.05-1.07)	1.00 (1.00-1.01)
	Very High	0.87 (0.86-0.88)	0.97 (0.96-0.98)	0.89 (0.88-0.9)	0.96 (0.95-0.96)
Difficulty Running Errands[3]	Low	1.01 (1.01-1.02)	1.05 (1.05-1.06)	0.99 (0.99-0.99)	1.02 (1.02-1.02)
	Moderate	0.96 (0.96-0.96)	0.89 (0.89-0.89)	1.00 (0.99-1.00)	0.93 (0.92-0.93)
	High	1.02 (1.02-1.03)	1.25 (1.25-1.26)	0.93 (0.93-0.94)	1.22 (1.21-1.23)
	Very High	0.61 (0.60-0.62)[S]	1.30 (1.29-1.32)	0.60 (0.59-0.61)[S]	1.21 (1.2-1.22)
Cancer Diagnosis[3]	Low	0.89 (0.89-0.89)	0.96 (0.96-0.96)	0.89 (0.89-0.89)	0.96 (0.96-0.96)
	Moderate	1.03 (1.03-1.03)	1.09 (1.09-1.1)	1.04 (1.04-1.04)	1.09 (1.09-1.09)
	High	0.93 (0.92-0.94)	0.93 (0.92-0.93)	1.07 (1.06-1.08)	1.01 (1-1.02)
	Very High	0.79 (0.78-0.8)	1.13 (1.12-1.15)	0.69 (0.68-0.70)[S]	0.98 (0.97-0.99)
Kidney Disease Diagnosis[3]	Low	0.95 (0.95-0.96)	0.96 (0.96-0.96)	0.99 (0.98-0.99)	0.99 (0.98-0.99)
	Moderate	0.97 (0.97-0.97)	0.98 (0.98-0.98)	1.03 (1.03-1.04)	1.03 (1.02-1.03)
	High	1.08 (1.07-1.09)	0.95 (0.94-0.96)	1.06 (1.05-1.07)	0.90 (0.89-0.90)
	Very High	0.76 (0.74-0.77)	0.87 (0.86-0.89)	0.77 (0.76-0.79)	0.86 (0.84-0.87)

Notes: Grey-shaded cells denote OR 95% CI overlaps 1.00 (i.e., not significant); Green-shaded cells denote Cohen's d $0.20 \leq d < .50$ or $0.50 \leq d < 0.80$ (superscript S and M, respectively).

[1]The adjusted binomial logistic regression model controlled for sex, age, race/ethnicity, education, veteran status, marital status, income, obesity, and smoking status.
[2]Low, Moderate, High, and Very High Lithium = 10-19.99, 20-29.99, 30-59.99, ≥60 µg/L, respectively; reference group: <10 µg/L (Very Low). The US Geological Survey was used to identify groundwater lithium concentrations, with exclusions made for wells that were unlikely potable water sources based on the methods of Lombard and colleagues [21].
[3]Reference group response "No."
[4]Reference group response <14 days.
[5]Reference group Likert Scale response ≤ 3.
[6]Reference group response ≥ 7 hours of sleep.

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