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Original Paper

Hydrometeorological Disasters and Climate-Sensitive Disease Burden in Pacific Island Countries: Evidence on Disease-Specific and Temporal Heterogeneity from a Multi-Database Panel Study

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Abstract

Background: *Pacific Island countries are highly vulnerable to hydrometeorological disasters, but comparable quantitative evidence on how such disasters affect climate-sensitive disease burden across countries remains limited. This study examined whether disaster-related health associations varied across diseases, outcome dimensions, and lag structures.*

Methods: *We conducted an ecological country-year panel study of 11 Pacific Island countries from 2000 to 2023 using data from the Global Burden of Disease Study, EM-DAT, the World Development Indicators, the Global Health Expenditure Database, and the ND-GAIN Country Index. Two-way fixed-effects models with country-clustered standard errors were used to estimate associations of disaster occurrence and disaster count with aggregate and disease-specific disease burden outcomes, with alternative incidence and death outcomes, lag terms, supplementary sensitivity analyses, wild cluster bootstrap tests for selected coefficients, and interaction models involving health expenditure and ND-GAIN readiness.*

Results: *No stable short-term average association was observed between hydrometeorological disasters and the aggregate climate-sensitive age-standardized DALY rate. In fully adjusted models, the coefficients for disaster occurrence and disaster count were 17.56 (95% CI: −12.43 to 47.54) and 9.39 (95% CI: −9.46 to 28.25), respectively. Disease-specific analyses revealed marked heterogeneity. The most robust finding was a delayed positive association between disaster occurrence and protein-energy malnutrition burden, with coefficients of 10.68 (95% CI: −0.13 to 21.49) at a 1-year lag and 13.65 (95% CI: 0.73 to 26.56) at a 2-year lag; both remained significant in wild cluster bootstrap tests (p = 0.026*

and p = 0.032). By contrast, diarrheal disease signals were weaker and not robust under stricter inference. Disaster-related signals were more evident for the aggregate climate-sensitive incidence rate than for the aggregate death rate, although the incidence association remained borderline under bootstrap testing.

Conclusions: *Hydrometeorological disasters were not associated with a stable short-term increase in the aggregate climate-sensitive DALY burden in Pacific Island countries, but their health effects showed clear disease-specific and time-dependent heterogeneity. The most robust evidence was concentrated in delayed nutrition-related burden, suggesting that climate-resilient health strategies in the Pacific should extend beyond emergency response to include stronger nutritional resilience, surveillance capacity, and cross-sector coordination.*

Keywords

Hydrometeorological disasters, climate-sensitive disease burden, Pacific Island countries, fixed-effects panel analysis

1. Introduction

Climate change is increasingly making hydrometeorological disasters a public health concern rather than only an environmental or economic problem [1]. The World Health Organization estimated that 3.6 billion people already live in areas highly vulnerable to climate change, and that climate change could cause about 250,000 additional deaths annually between 2030 and 2050 from undernutrition, malaria, diarrhoea, and heat stress [2]. Recent global assessments have further shown that rising temperatures, floods, storms, droughts, and shifting infectious disease risks are intensifying climate-related health threats worldwide [3-4]. These patterns suggest that hydrometeorological disasters may affect health not only through direct injury and mortality, but also through disruptions to food systems, water and sanitation conditions, disease transmission environments, and access to care [1-2].

Pacific Island countries provide a particularly important setting for examining these risks because high exposure is combined with limited adaptive capacity [5]. Many of these countries consist of small and widely dispersed island populations with fragile infrastructure, narrow economic bases, and health systems operating across remote territories [5-6]. Regional studies have identified extreme weather, food and water insecurity, vector-borne disease, and health-system constraints as major climate-sensitive health concerns in the Pacific [5-7]. At the same time, quantitative evidence remains limited and unevenly distributed across countries [6]. This combination of high vulnerability and limited comparable evidence makes Pacific Island countries a critical context for assessing how hydrometeorological disasters shape climate-sensitive disease burden over time.

Existing evidence does not yet adequately answer this question. Much of the Pacific literature has focused on vulnerability assessments, adaptation priorities, or broad evidence mapping rather than comparable multi-country quantitative analysis [5-6]. Outside the Pacific, studies have shown that hydrometeorological conditions can shape dengue risk and post-disaster infectious morbidity over short

and often non-linear time windows [8-9]. These designs, however, usually rely on subannual or event-based data and focus on single outcomes. As a result, little comparative evidence is available on whether hydrometeorological disasters in Pacific Island countries are associated with aggregate climate-sensitive disease burden, whether effects differ across diseases, or whether delayed associations are more visible in some outcomes than in others [6,10].

This study addressed these gaps by linking data from the Global Burden of Disease Study, EM-DAT, the World Development Indicators, the Global Health Expenditure Database, and the ND-GAIN Country Index in a country-year panel of 11 Pacific Island countries from 2000 to 2023. It examined whether hydrometeorological disasters were associated with aggregate climate-sensitive disease burden, whether associations differed across dengue, diarrheal diseases, and protein-energy malnutrition, and whether disaster-related signals were more evident in burden, incidence, or mortality outcomes across different lag structures. By integrating multiple databases and comparing outcomes, diseases, and time dimensions within a unified analytical framework, the study aimed to provide more comparable quantitative evidence for a region where climate-health vulnerability is high but harmonized longitudinal evidence remains scarce.

2. Materials and Methods

2.1 Study Design and Data Sources

This study used an ecological panel design based on annual country-level observations from 11 Pacific Island countries between 2000 and 2023. The analytical sample included Fiji, Kiribati, Marshall Islands, the Federated States of Micronesia, Nauru, Palau, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. Papua New Guinea was not included because its population size, geographic scale, and health system structure differ substantially from those of the smaller Pacific Island states, which would have reduced sample comparability. Data were compiled from five publicly available sources. Disease burden data were obtained from the Global Burden of Disease Study 2023, which provides standardized estimates of mortality and non-fatal health loss across countries and years [10-11]. Disaster exposure data were obtained from the Emergency Events Database (EM-DAT), a global disaster database that records the occurrence and characteristics of major disaster events using harmonized international reporting criteria [12]. Macroeconomic and demographic covariates were drawn from the World Development Indicators database maintained by the World Bank [13]. Health financing variables were obtained from the World Health Organization's Global Health Expenditure Database [14]. National adaptation-related indicators were obtained from the Notre Dame Global Adaptation Initiative Country Index, which reports vulnerability and readiness measures for climate adaptation at the country level [15]. All datasets were harmonized by country and year and then merged into a unified country-year panel. Country names were standardized across databases using a predefined crosswalk to ensure consistent identifiers. Only observations with valid country-year matches were retained. The final analytical dataset contained 264 country-year observations.

2.2 Outcomes, Exposure, and Covariates

The study considered three layers of outcome variables. The first was the overall climate-sensitive age-standardized DALY rate, constructed by summing the age-standardized DALY rates for dengue, diarrheal diseases, and protein-energy malnutrition using annual country-level estimates from the Global Burden of Disease Study [10-11]. This aggregate indicator was used to characterize the overall burden pattern at the national level. The second consisted of disease-specific DALY outcomes for dengue, diarrheal diseases, and protein-energy malnutrition, which were used in the main disease-level analyses to assess heterogeneity across conditions and lag structures. The third included two alternative aggregate outcomes, namely the overall climate-sensitive age-standardized incidence rate and the overall climate-sensitive age-standardized death rate, which were used to evaluate whether disaster-related signals were more readily observed in morbidity or mortality dimensions [10-11]. The main exposure variables were derived from EM-DAT and focused on hydrometeorological disasters [12]. Following the EM-DAT event classification, droughts, floods, and storms were retained and aggregated to the annual country level. Two primary exposure indicators were used in the main models. The first was a disaster occurrence dummy, coded as 1 if at least one hydrometeorological disaster occurred in a given country-year and 0 otherwise. The second was the annual disaster count, defined as the number of hydrometeorological disaster events recorded in the same country-year. Several supplementary disaster-intensity indicators were also constructed. These included the proportion of the population affected by disasters, disaster-related deaths per 100,000 population, and a composite severity indicator based on standardized disaster count, deaths per 100,000, and affected population share. Because the affected-share measure could exceed 1 when multiple disasters were recorded within the same country-year, a capped version was additionally created for sensitivity analysis. Covariates were selected to capture economic conditions, demographic structure, health-system inputs, and adaptive capacity. The main covariates included log gross domestic product per capita and urban population share from the World Development Indicators database [13], current health expenditure as a percentage of gross domestic product from the Global Health Expenditure Database [14], and ND-GAIN readiness from the ND-GAIN Country Index [15]. Population size was also retained for descriptive purposes and for constructing disaster-intensity measures. In the interaction models, health expenditure and ND-GAIN readiness were mean-centered to improve interpretability of the main and interaction terms.

2.3 Statistical Analysis

The statistical analysis proceeded from aggregate to disease-specific outcomes. Aggregate models were first used to examine whether hydrometeorological disaster exposure was associated with the overall climate-sensitive age-standardized DALY rate at the national annual level. Disease-specific models were then estimated separately for dengue, diarrheal diseases, and protein-energy malnutrition and served as the main analyses for identifying heterogeneity across conditions and lag structures. Alternative-outcome models further replaced the aggregate DALY outcome with the overall climate-sensitive age-standardized incidence rate and age-standardized death rate in order to assess whether disaster-related

signals were more clearly reflected in morbidity or mortality dimensions. Descriptive statistics were first used to summarize the distribution of outcomes, exposures, and covariates. Time-trend figures were generated for the overall climate-sensitive DALY rate, annual disaster count, and ND-GAIN readiness, and country-level summary statistics were examined to assess cross-country heterogeneity. The main regression models were specified as two-way fixed-effects linear models with country fixed effects and year fixed effects. Country fixed effects were used to control for time-invariant differences across countries, whereas year fixed effects captured common period shocks affecting all countries [16]. Standard errors were clustered at the country level to account for serial correlation and within-country dependence over time [16]. The primary disaster exposures were disaster occurrence and annual disaster count. Temporal dynamics were assessed by sequentially introducing one-year and two-year lagged disaster terms. In line with the observed disease-specific response patterns and biological plausibility, contemporaneous and one-year lags were emphasized for dengue and diarrheal disease models, whereas one-year and two-year lags were examined more closely for protein-energy malnutrition models. Several supplementary analyses were conducted to evaluate robustness. Control-specification sensitivity analyses compared fixed-effects-only models, models with basic economic controls, and fully adjusted models. Lower-bound sensitivity analyses were performed for disaster-intensity indicators by recoding missing disaster-year intensity values as zero and reconstructing the corresponding intensity measures. Because the number of country clusters was limited, wild cluster bootstrap tests were additionally applied to selected near-significant coefficients to assess the robustness of statistical inference [17-18]. Interaction models were further estimated to test whether disaster–health associations varied by health expenditure or ND-GAIN readiness. Exact p-values and 95% confidence intervals were extracted from fitted model objects for narrative reporting, whereas regression tables present coefficients and clustered standard errors for readability. All analyses were conducted in R [19], and statistical inference was based on two-sided tests with a significance level of 0.05.

3. Results

Between 2000 and 2023, the overall climate-sensitive disease burden in Pacific Island countries showed a sustained downward trend, with the mean climate-sensitive DALY rate declining steadily from a relatively high level at the beginning of the study period to a markedly lower level by the end. In contrast, disaster frequency fluctuated over time and did not exhibit a clear unidirectional trend, with comparatively higher levels observed only in selected years. Meanwhile, mean ND-GAIN readiness remained broadly stable during the earlier years of the study period and increased steadily after 2015. Cross-country variation was also evident. Kiribati, the Federated States of Micronesia, Nauru, and Vanuatu had comparatively high mean climate-sensitive DALY rates, whereas Tonga, Samoa, and Fiji showed relatively low levels. Notably, countries with more frequent disasters did not necessarily experience a higher average disease burden. For example, Fiji had the highest mean disaster count but a comparatively low average burden, whereas Nauru exhibited a relatively high average burden despite

having no recorded disasters. Overall, climate-sensitive disease burden, disaster exposure, and national preparedness followed distinct temporal patterns over the study period (Figures 1-3).

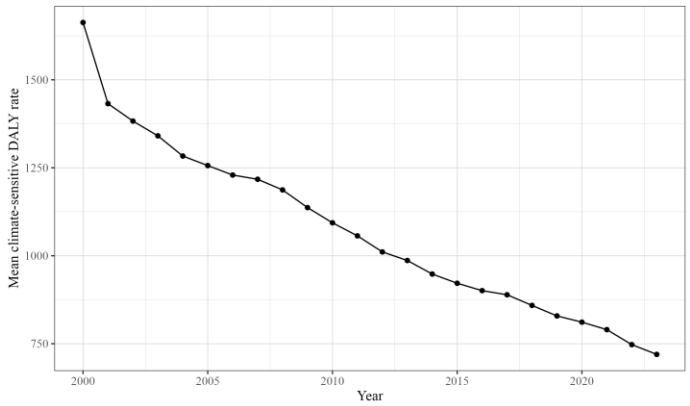

Figure 1. Trend of Mean Climate-sensitive DALY Rate in PICs, 2000–2023

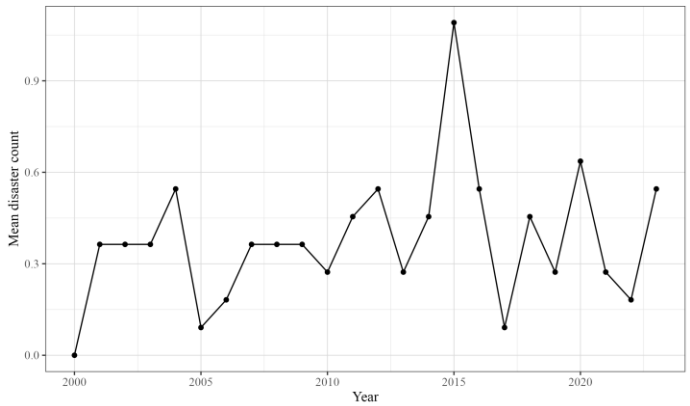

Figure 2. Trend of Mean Disaster Count in PICs, 2000–2023

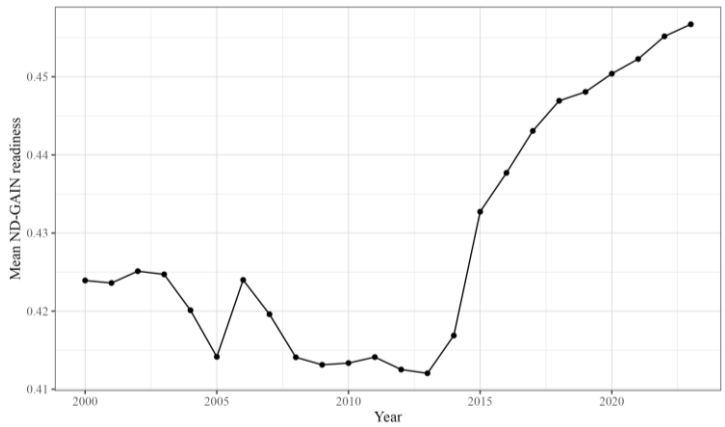

Figure 3. Trend of Mean ND-GAIN Readiness in PICs, 2000–2023

3.1 Main Model Results

3.1.1 Overall Climate-sensitive DALY Results

Table 1 presents the fixed-effects estimates for the association between hydrometeorological disasters and overall climate-sensitive DALY rates. In the fully adjusted baseline models, both disaster occurrence and disaster count were positively associated with the composite DALY outcome, although neither association reached statistical significance. The coefficient for disaster occurrence was 17.56 (95% CI: −12.43 to 47.54; p = 0.221), and the corresponding coefficient for disaster count was 9.39 (95% CI: −9.46 to 28.25; p = 0.293). After inclusion of 1-year lag terms, the contemporaneous and lagged coefficients remained positive but imprecisely estimated. In the lagged specifications, the coefficient for contemporaneous disaster occurrence was 19.01 (95% CI: −15.01 to 53.03; p = 0.241), while the coefficient for the 1-year lagged disaster occurrence term was 23.22 (95% CI: −6.48 to 52.93; p = 0.112). Similarly, the corresponding coefficients for disaster count were 8.82 (95% CI: −17.15 to 34.79; p = 0.467) for the contemporaneous term and 14.01 (95% CI: −4.53 to 32.56; p = 0.123) for the 1-year lagged term. Overall, the association between hydrometeorological disasters and aggregate climate-sensitive DALY rates was positive in direction but estimated with limited precision.

Table 1. Fixed-effects Estimates of Hydrometeorological Disasters and Overall Climate-sensitive DALY Rates

Variable	M1	M2	M3	M4
Disaster occurrence	17.6 (13.5)	—	19.0 (15.3)	—
Disaster count	—	9.39 (8.46)	—	8.82 (11.7)
Lag 1 disaster occurrence	—	—	23.2 (13.3)	—
Lag 1 disaster count	—	—	—	14.0 (8.32)
Economic controls	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	264	264	253	253
Adjusted R^2	0.916	0.916	0.939	0.939

Notes: Cluster-robust standard errors at the country level are reported in parentheses.

All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Health system control is health expenditure (% GDP). Readiness control is ND-GAIN readiness. † p < 0.10, * p < 0.05, ** p < 0.01. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S9 Table.

3.1.2 Cause-specific DALY Results

Table 2 reports the cause-specific DALY results. For diarrheal diseases, the estimated coefficients were consistently positive across the contemporaneous and 1-year lag models, but none met conventional significance thresholds. In the fully adjusted models, the coefficient for contemporaneous disaster occurrence was 8.83 (95% CI: −13.97 to 31.62; p = 0.408), and the corresponding coefficient for disaster count was 6.17 (95% CI: −8.42 to 20.77; p = 0.368). After inclusion of lagged terms, the coefficient for the 1-year lagged disaster occurrence term was 12.92 (95% CI: −10.95 to 36.79; p = 0.255), and that for the 1-year lagged disaster count term was 10.45 (95% CI: −4.00 to 24.89; p = 0.138). These estimates suggested a positive but statistically imprecise association between disaster exposure and diarrheal DALY rates at the annual country-level scale. Although the 2-year lagged disaster-count term in the extended specification was positive in the conventional clustered-SE model, this signal did not remain significant after wild cluster bootstrap testing, indicating limited robustness.

For protein-energy malnutrition (PEM), the contemporaneous disaster coefficients were also positive but did not reach statistical significance. In the 1-year lag models, the coefficient for lagged disaster occurrence was 10.68 (95% CI: −0.13 to 21.49; p = 0.052), while in the 2-year lag specification, the coefficient for lagged disaster occurrence increased to 13.65 (95% CI: 0.73 to 26.56; p = 0.040). By contrast, the lagged disaster count terms for PEM remained positive but statistically non-significant, including the 2-year lagged disaster count coefficient of 5.97 (95% CI: −4.41 to 16.36; p = 0.229). Importantly, wild cluster bootstrap tests confirmed that the delayed occurrence effects for PEM remained statistically significant at both the 1-year lag (bootstrap p = 0.026) and the 2-year lag (bootstrap p = 0.032), supporting a comparatively robust delayed association between hydrometeorological disasters and nutrition-related disease burden. Taken together, the cause-specific models indicated substantial heterogeneity across disease categories, with the clearest delayed association observed for PEM.

Table 2. Fixed-effects Estimates of Hydrometeorological Disasters and Cause-specific DALY Rates

Variable	M1	M2	M3	M4
Panel A. Diarrheal DALY rates				
Disaster occurrence	8.83 (10.2)	—	10.2 (11.9)	—
Disaster count	—	6.17 (6.55)	—	5.66 (8.53)
Lag 1 disaster occurrence	—	—	12.9 (10.7)	—
Lag 1 disaster count	—	—	—	10.4 (6.48)
Economic controls	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Observations	264	264	253	253		
Adjusted R^2	0.891	0.891	0.933	0.933		
Variable	M1	M2	M3	M4	M5	M6
Panel B. Protein-energy malnutrition DALY rates						
Disaster occurrence	5.92 (4.24)	—	5.93 (4.33)	—	9.05 (5.87)	—
Disaster count	—	2.57 (3.49)	—	2.57 (4.00)	—	3.80 (5.58)
Lag 1 disaster occurrence	—	—	10.7† (4.85)	—	10.6† (5.04)	—
Lag 1 disaster count	—	—	—	4.41 (4.00)	—	4.52 (4.45)
Lag 2 disaster occurrence	—	—	—	—	13.6* (5.80)	—
Lag 2 disaster count	—	—	—	—	—	5.97 (4.66)
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	264	264	253	253	242	242
Adjusted R^2	0.953	0.953	0.956	0.956	0.958	0.958

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Health system control is health expenditure (% GDP). Readiness control is ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S9 Table.

3.1.3 Alternative Outcome Analysis Using Incidence Rates

Table 3 presents the corresponding models using overall climate-sensitive incidence rates as the outcome. Compared with the composite DALY models, the incidence models yielded consistently larger positive coefficients for both disaster occurrence and disaster count. In the baseline specifications, the coefficient for disaster occurrence was 808.70 (95% CI: −277.99 to 1,895.39; $p = 0.128$), while the coefficient for disaster count was 405.18 (95% CI: −302.92 to 1,113.28; $p = 0.231$). After including 1-year lag terms, the coefficient for contemporaneous disaster occurrence increased to 923.15 (95% CI: −229.40 to 2,075.71; $p = 0.105$), and the corresponding lagged disaster occurrence coefficient was 640.70 (95% CI: −418.11 to 1,699.50; $p = 0.207$). Likewise, the coefficient for contemporaneous disaster count was 485.73 (95% CI: −318.23 to 1,289.70; $p = 0.208$), and the coefficient for the 1-year lagged disaster count term was 433.43 (95% CI: −265.88 to 1,132.74; $p = 0.197$). Although these estimates remained statistically imprecise, the incidence models showed a more consistently positive pattern than the corresponding DALY models. In the extended lag specification, the contemporaneous disaster-occurrence term remained only borderline significant under wild cluster bootstrap inference (bootstrap $p = 0.094$),

suggesting weak rather than definitive evidence that disaster shocks may first be reflected in the incidence dimension.

Table 3. Fixed-effects Estimates of Hydrometeorological Disasters and Overall Climate-sensitive Incidence Rates

	M1	M2	M3	M4
Disaster occurrence	808.7 (487.7)	—	923.2 (517.3)	—
Disaster count	—	405.2 (317.8)	—	485.7 (360.8)
Lag 1 disaster occurrence	—	—	640.7 (475.2)	—
Lag 1 disaster count	—	—	—	433.4 (313.9)
Economic controls	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	264	264	253	253
Adjusted R^2	0.905	0.904	0.910	0.909

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Health system control is health expenditure (% GDP). Readiness control is ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S9 Table.

3.1.4 Supplementary and Robustness Analyses

The Supplementary Tables present several additional analyses. First, in the 2-year lag models for overall climate-sensitive DALY rates, the 2-year lagged disaster-occurrence coefficient and the corresponding 2-year lagged disaster-count coefficient were both positive in the conventional clustered-SE models, suggesting delayed associations estimated with limited precision. However, wild cluster bootstrap testing indicated that the delayed disaster-occurrence coefficient for the overall DALY outcome remained only borderline significant, implying weak rather than robust evidence at the aggregate level. Second, dengue-specific models showed no stable associations across either contemporaneous or lagged specifications; all corresponding coefficients were small and statistically non-significant. Third, alternative exposure definitions and alternative functional forms did not materially alter the overall conclusion. The coefficient for affected-share (capped) was 52.81 (95% CI: −160.22 to 265.85; $p = 0.593$), the coefficient for severity-core (capped) was 3.53 (95% CI: −3.08 to 10.13; $p = 0.262$), the coefficient for disaster occurrence in the log-DALY model was 0.002 (95% CI: −0.015 to 0.019; $p = 0.792$), and the

corresponding disaster-count coefficient was 0.003 (95% CI: −0.006 to 0.012; p = 0.481).

Further sensitivity analyses by control specification showed that disaster coefficients were generally larger in models with only basic economic controls than in the fully adjusted models. For example, the disaster-occurrence coefficient for overall incidence was 1097.39 (95% CI: −220.53 to 2,415.30; p = 0.093) in the basic model, compared with 808.70 (95% CI: −277.99 to 1,895.39; p = 0.128) in the fully adjusted model. A similar pattern was observed for diarrheal DALY, where the disaster-count coefficient was 15.23 (95% CI: −3.67 to 34.13; p = 0.103) in the basic model and 6.17 (95% CI: −8.42 to 20.77; p = 0.368) in the fully adjusted model. Lower-bound sensitivity analyses for missing disaster-intensity measures showed that replacing missing disaster-year intensity values with zeros did not materially change the direction or magnitude of the coefficients for either diarrheal DALY or PEM DALY. Finally, wild cluster bootstrap tests for selected near-significant coefficients showed clear heterogeneity in robustness: the delayed occurrence effects for PEM remained statistically significant at both the 1-year and 2-year lags, the corresponding signal for diarrheal DALY did not remain significant, and the contemporaneous disaster-occurrence effect in the incidence model remained only borderline significant. Overall, these supplementary analyses reinforced the conclusion that the most robust delayed association was concentrated in PEM, whereas evidence for aggregate DALY and diarrheal DALY remained comparatively weaker. In addition, interaction models provided no clear evidence that health expenditure buffered disaster effects. Only in the overall incidence model was the interaction between disaster occurrence and ND-GAIN readiness significantly positive, suggesting that disaster-related changes in incidence were more readily observed in higher-readiness countries. Given the ecological scale of the analysis and the direction of the estimate, this pattern is more plausibly interpreted as reflecting differences in surveillance, diagnosis, and reporting capacity rather than a harmful amplifying effect of readiness itself.

4. Discussion

Our study provides one of the first multi-country panel-data assessments of the association between hydrometeorological disasters and climate-sensitive disease burden across 11 Pacific Island countries from 2000 to 2023. Several findings merit further discussion. First, although the overall climate-sensitive DALY rate declined over the study period, we did not observe a stable short-term average association between disaster exposure and the composite DALY outcome at the national annual level. Rather than indicating an absence of climate-related health effects, this pattern more likely reflects the limited quantitative evidence currently available for Pacific Island settings [6], the ecological nature of country-year analyses, and the fact that aggregate burden measures may average over diseases with distinct transmission pathways and temporal responses [20]. Previous work has likewise emphasized that climate–health evidence in the Pacific remains methodologically limited and unevenly distributed across countries, while broader regional assessments have shown that small island settings face persistent climate-sensitive health vulnerabilities despite ongoing improvements in preparedness and adaptation

capacity [7]. In this context, our results suggested that weak aggregate associations should not be interpreted as evidence of no effect, but instead as a signal that disaster-related health impacts in Pacific Island countries are likely to be heterogeneous, temporally uneven, and only partially captured by composite annual indicators [6-7].

Several factors may help explain why the aggregate association between hydrometeorological disasters and overall climate-sensitive DALY rates remained weak and imprecisely estimated in our models. The composite DALY indicator combined dengue, diarrheal diseases, and protein-energy malnutrition, three outcomes that differ substantially in biological latency, transmission dynamics, and pathways of disaster-related vulnerability. Averaging across these conditions at the national annual level likely diluted disease-specific responses that operate on much shorter temporal scales for acute infectious outcomes, but over longer and more cumulative pathways for nutrition-related burden [7]. The annual country-level design also masked subnational, seasonal, and event-specific variation in both exposure and health response [6]. This limitation is especially relevant in Pacific Island settings, where climate information, monitoring capacity, and service provision remain uneven across dispersed island populations [20]. Our exposure measures, particularly disaster occurrence and disaster count, were useful for identifying broad patterns, but they could not fully capture disaster intensity, duration, geographic extent, or the degree of disruption to food systems, water infrastructure, and service delivery. Evidence from environmental epidemiology has further shown that climate-sensitive infectious outcomes often display non-linear and delayed responses that are more readily detected at finer temporal scales than in annual ecological panels[8]. The weak aggregate DALY results in our study should therefore be interpreted as a limitation of scale and aggregation rather than as evidence that disaster-related health impacts were absent.

Disease-specific models clarified that the health consequences of hydrometeorological disasters were not uniform across climate-sensitive conditions. The most robust delayed association was observed for protein-energy malnutrition, whereas the evidence for diarrheal disease remained weaker, and the dengue models showed no stable relationship. This pattern is epidemiologically plausible. Nutrition-related burdens are more likely to emerge through indirect and cumulative pathways, including crop losses, food price instability, disrupted local supply chains, and prolonged household food insecurity [21]. In Pacific Island countries and territories, climate change has repeatedly been linked to vulnerabilities in food systems, fisheries, and nutritional security, making nutrition-related outcomes particularly sensitive to shocks that extend beyond the immediate disaster period [7,22]. By contrast, dengue and many diarrheal outcomes often respond over much shorter temporal windows, with risks shaped by local hydrometeorological conditions, vector ecology, water contamination, sanitation breakdown, and the timing of post-disaster recovery [8-9]. Associations of this kind are therefore more likely to be detected in studies using subannual or event-based data than in annual national panels. The fact that the delayed PEM coefficients remained significant under wild cluster bootstrap, whereas the corresponding signal for diarrheal DALY did not, further suggested that the nutrition pathway captured by our models was more stable than the acute infectious-disease pathway at the scale of analysis used in this study.

The positive interaction between disaster occurrence and ND-GAIN readiness on incidence rates warrants cautious interpretation. At face value, higher readiness was associated with a stronger positive disaster–incidence relationship, but this pattern should not be read as evidence that readiness amplified the underlying biological harm of disasters. In small-island settings, higher readiness scores may instead proxy stronger surveillance systems, better diagnostic access, and more complete reporting infrastructure, making post-disaster morbidity more likely to be detected and recorded [6-7]. This interpretation is consistent with broader assessments showing that climate information systems, early warning capacity, and health data infrastructures remain uneven across Pacific Island and wider Small Island Developing State contexts [20]. The lack of a significant buffering interaction for general health expenditure pointed in the same direction. Aggregate spending levels alone may be too crude to capture the operational dimensions of resilience that matter most during and after disasters, including outreach continuity, transport logistics, nutritional surveillance, and case detection. The incidence interaction therefore appears more plausibly to reflect differential observability of disaster-related morbidity than a true amplifying effect of readiness on health risk.

These findings have several implications for climate-health policy in Pacific Island countries. The delayed and comparatively robust association observed for protein-energy malnutrition suggested that disaster response should not be framed only in terms of short-term emergency relief, but also in terms of sustained protection of food security, nutritional surveillance, and continuity of primary care after hydrometeorological shocks [7]. In small-island settings where food systems, fisheries, transport links, and health services are tightly interconnected, climate-resilient adaptation is likely to be most effective when disaster risk reduction, nutrition policy, and health-system planning are addressed together rather than in isolation [20]. The weak and non-significant buffering role of general health expenditure also carried an important policy message. Aggregate spending indicators may not adequately reflect the forms of reserve capacity, flexibility, and preparedness that determine whether health systems can absorb and adapt to rare but high-impact shocks [23]. This is consistent with broader work showing that the resource demands imposed by climate change can grow nonlinearly and place disproportionate pressure on lower-income health systems, even when overall expenditure levels appear stable [24]. The study also contributes methodologically beyond a conventional single-database burden analysis. By integrating GBD, EM-DAT, WDI, GHED, and ND-GAIN into a unified country-year panel, and by combining disease-specific modelling with lag structures, control-specification sensitivity analyses, lower-bound missingness checks, and wild cluster bootstrap inference, it was possible to distinguish weak aggregate signals from more robust disease-specific delayed associations. In that sense, the present study supports a more targeted adaptation agenda for Pacific Island countries, one that prioritises long-term nutritional resilience, surveillance capacity, and cross-sector coordination rather than assuming that higher aggregate spending alone will buffer disaster-related health risks.

This study should be interpreted in light of several limitations. The analysis was conducted at the national annual level, which may have masked substantial subnational and seasonal heterogeneity in both disaster

exposure and health response. This issue is particularly relevant in Pacific Island settings, where climate-sensitive health risks often vary across islands and over shorter time scales than those captured in annual panel data [1]. The disaster indicators derived from EM-DAT and the outcome measures based on GBD estimates were appropriate for multi-country comparative analysis, but both sources may involve measurement error. EM-DAT may undercapture smaller or localised events, while GBD outcomes are model-based estimates rather than direct surveillance counts [2]. The number of country clusters was also limited, which reduced statistical power and requires cautious interpretation of borderline-significant findings, especially for interaction terms and secondary outcomes. Despite these limitations, the consistency of the main disease-specific pattern across multiple supplementary analyses supports the credibility of the central finding on delayed PEM burden.

5. Conclusion

Using a multi-database country-year panel of 11 Pacific Island countries from 2000 to 2023, this study found that hydrometeorological disasters were not associated with a stable short-term average increase in the composite climate-sensitive DALY rate at the aggregate level, but substantial heterogeneity emerged across outcomes, diseases, and time dimensions. The most robust finding was a delayed positive association between disaster occurrence and protein-energy malnutrition burden, with significant effects observed at one-year and two-year lags, whereas evidence for overall incidence remained suggestive, and the corresponding signals for diarrheal disease were not robust under more stringent inference. These results indicate that the health consequences of hydrometeorological disasters in Pacific Island countries are not fully captured by aggregate burden indicators alone and are more clearly reflected in specific disease categories, particularly nutrition-related outcomes. Overall, the study suggests that disaster-related health risks in Pacific Island countries are disease-specific, time-dependent, and partly conditioned by differences in national capacity, implying that climate-resilient health strategies in the Pacific should extend beyond emergency response to place greater emphasis on nutritional resilience, surveillance capacity, and cross-sector coordination across health, food, and disaster governance systems.

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Appendix

S1 Table. Two-year lag fixed-effects models for overall climate-sensitive DALY rates

Variable	M5	M6
Disaster occurrence	26.7 (19.6)	—
Disaster count	—	9.98 (15.2)
Lag 1 disaster occurrence	22.0 (13.0)	—
Lag 1 disaster count	—	13.4 (9.58)
Lag 2 disaster occurrence	32.0† (15.4)	—
Lag 2 disaster count	—	20.1† (9.10)

Economic controls	Yes	Yes
Health system controls	Yes	Yes
Readiness controls	Yes	Yes
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	242	242
Adjusted R^2	0.944	0.943

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S2 Table. Fixed-effects estimates of hydrometeorological disasters and dengue DALY rates

Variable	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
Disaster occurrence	2.81 (1.92)	—	2.84 (1.97)	—	2.63 (2.18)	—
Disaster count	—	0.656 (0.928)	—	0.597 (0.974)	—	0.497 (1.18)
Lag 1 disaster occurrence	—	—	-0.380 (1.45)	—	-0.343 (1.44)	—
Lag 1 disaster count	—	—	—	-0.842 (1.79)	—	-0.766 (1.83)
Lag 2 disaster occurrence	—	—	—	—	1.67 (1.92)	—
Lag 2 disaster count	—	—	—	—	—	2.08 (2.15)
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	264	264	253	253	242	242
Adjusted R^2	0.383	0.380	0.369	0.367	0.355	0.356

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S3 Table. Extended lag models for diarrheal DALY rates

Variable	M5	M6
Disaster occurrence	15.0 (14.7)	—
Disaster count	—	5.69 (10.6)
Lag 1 disaster occurrence	11.7 (10.3)	—
Lag 1 disaster count	—	9.67 (7.09)
Lag 2 disaster occurrence	16.6 (11.8)	—
Lag 2 disaster count	—	12.1† (6.39)
Economic controls	Yes	Yes
Health system controls	Yes	Yes
Readiness controls	Yes	Yes
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	242	242
Adjusted R^2	0.938	0.938

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S4 Table. Fixed-effects estimates of hydrometeorological disasters and overall climate-sensitive death rates

Variable	M1	M2	M3	M4	M5	M6
Disaster occurrence	0.168 (0.364)	—	0.262 (0.415)	—	0.534 (0.528)	—
Disaster count	—	0.121 (0.261)	—	0.159 (0.315)	—	0.238 (0.400)
Lag 1 disaster occurrence	—	—	0.365 (0.398)	—	0.397 (0.385)	—
Lag 1 disaster count	—	—	—	0.276 (0.271)	—	0.301 (0.287)
Lag 2 disaster occurrence	—	—	—	—	0.634 (0.449)	—
Lag 2 disaster count	—	—	—	—	—	0.362 (0.257)
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	264	264	253	253	242	242

Adjusted R^2	0.951	0.951	0.963	0.963	0.967	0.967

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S5 Table. Two-year lag fixed-effects models for overall climate-sensitive incidence rates

Variable	M5	M6
Disaster occurrence	1,223.8† (667.3)	—
Disaster count	—	622.4 (455.1)
Lag 1 disaster occurrence	731.9 (479.9)	—
Lag 1 disaster count	—	524.5 (349.1)
Lag 2 disaster occurrence	872.2 (562.6)	—
Lag 2 disaster count	—	758.1 (419.1)
Economic controls	Yes	Yes
Health system controls	Yes	Yes
Readiness controls	Yes	Yes
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	242	242
Adjusted R^2	0.914	0.914

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S6 Table. Robustness checks using alternative exposure definitions and functional forms

Variable	M7	M8	M9	M10
Affected share (capped)	52.8 (95.6)	—	—	—
Severity core (capped)	—	3.53 (2.96)	—	—
Disaster occurrence	—	—	0.002 (0.008)	—
Disaster count	—	—	—	0.003 (0.004)
Outcome form	Level DALY	Level DALY	Log DALY	Log DALY
Economic controls	Yes	Yes	Yes	Yes

Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	246	208	264	264
Adjusted R^2	0.912	0.908	0.986	0.986

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S7 Table. Sensitivity analysis by control-variable specification

Specification	**FE only**	**Basic controls**	**Full controls**
Panel A. Overall climate-sensitive DALY rate ~ disaster occurrence			
Disaster occurrence	21.2 (24.7)	40.2 (24.2)	17.6 (13.5)
Economic controls	No	Yes	Yes
Health system controls	No	No	Yes
Readiness controls	No	No	Yes
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	264	264	264
Adjusted R^2	0.887	0.898	0.916
Panel B. Overall climate-sensitive incidence rate ~ disaster occurrence			
Disaster occurrence	768.9 (645.9)	1,097.4† (591.5)	808.7 (487.7)
Economic controls	No	Yes	Yes
Health system controls	No	No	Yes
Readiness controls	No	No	Yes
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	264	264	264
Adjusted R^2	0.884	0.893	0.905
Panel C. Diarrheal DALY rate ~ disaster count			
Disaster count	11.2 (9.51)	15.2 (8.48)	6.17 (6.55)
Economic controls	No	Yes	Yes
Health system controls	No	No	Yes

Readiness controls	No	No	Yes
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	264	264	264
Adjusted R^2	0.855	0.872	0.891
Panel D. PEM DALY rate ~ disaster occurrence			
Disaster occurrence	9.25 (6.34)	12.8 (8.60)	5.92 (4.24)
Economic controls	No	Yes	Yes
Health system controls	No	No	Yes
Readiness controls	No	No	Yes
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	264	264	264
Adjusted R^2	0.940	0.942	0.953

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S8 Table. Lower-bound sensitivity analysis for missing disaster-intensity measures

Variable	Original affected-share model	Lower-bound affected-share model	Original severity model	Lower-bound severity model
Panel A. Diarrheal DALY rate				
Affected share	49.7 (62.8)	38.4 (61.7)	—	—
Severity core	—	—	2.74 (2.39)	2.12 (2.84)
Economic controls	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	246	264	208	264
Adjusted R^2	0.885	0.891	0.879	0.891
Panel B. Protein-energy malnutrition DALY rate				
Affected share	0.974 (36.7)	0.957 (35.4)	—	—
Severity core	—	—	1.12 (1.19)	0.748 (1.52)

Economic controls	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	246	264	208	264
Adjusted R^2	0.951	0.953	0.952	0.953

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Economic controls include log GDP per capita and urban population share. Full specifications also control for health expenditure (% GDP) and ND-GAIN readiness. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. Inference for selected near-significant coefficients was further evaluated using wild cluster bootstrap; see S Table9.

S9 Table. Wild cluster bootstrap inference for selected near-significant coefficients

Outcome / model	Coefficient tested	Estimate	Bootstrap type	Bootstrap p-value	95% CI	Interpretation
Overall climate-sensitive DALY, M5	Lag 2 disaster occurrence	31.95	Webb	0.102	−6.79 to 69.83	Weak evidence only
Overall climate-sensitive incidence, M5	Disaster occurrence	1223.84	Webb	0.094	−171.37 to 2942.73	Borderline evidence
Diarrheal DALY, M6	Lag 2 disaster count	12.06	Webb	0.189	−8.04 to 32.06	Not robust
PEM DALY, M3	Lag 1 disaster occurrence	10.68	Webb	0.026	0.91 to 23.30	Robust delayed association
PEM DALY, M5	Lag 2 disaster occurrence	13.65	Webb	0.032	0.91 to 28.00	Robust delayed association

Notes: Wild cluster bootstrap tests were implemented with one-way clustering at the country level. The table reports bootstrap-based p-values and confidence intervals for selected coefficients that were near-significant in the conventional clustered-SE models.

S10 Table. Fixed-effects interaction models of hydrometeorological disasters with health expenditure and ND-GAIN readiness

Variable	M1	M2	M3	M4
	PEM DALY	PEM DALY	Overall incidence rate	Overall incidence rate
Disaster occurrence	6.53 (5.78)	8.25 (6.90)	1,051.3 (599.9)	1,385.4* (522.8)
Health expenditure (centered)	0.270 (2.47)	—	336.0 (204.9)	—

ND-GAIN readiness	1,141.0† (606.8)	—	39,468.6 (41,368.0)	—
Disaster × health expenditure	0.529 (1.73)	—	210.1 (147.2)	—
ND-GAIN readiness (centered)	—	1,116.7† (604.1)	—	33,632.4 (40,950.3)
Health expenditure (% GDP)	—	0.322 (2.63)	—	354.9 (217.3)
Disaster × readiness	—	103.2 (171.1)	—	25,509.6* (10,601.0)
Log GDP per capita	-33.6 (68.6)	-33.2 (68.2)	2,482.5 (4,373.7)	2,480.2 (4,399.0)
Urban population share	-1.78 (5.90)	-1.96 (5.99)	-360.0 (380.4)	-402.2 (370.9)
Economic controls	Yes	Yes	Yes	Yes
Health system controls	Yes	Yes	Yes	Yes
Readiness controls	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	264	264	264	264
Adjusted R^2	0.953	0.953	0.905	0.907

Notes: Cluster-robust standard errors at the country level are reported in parentheses. All models include country and year fixed effects. Centered variables were mean-centered before estimation. Economic controls include log GDP per capita and urban population share. In the health-expenditure interaction models, ND-GAIN readiness is additionally included as a control. In the readiness interaction models, health expenditure (% GDP) is additionally included as a control. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$.