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Assessed Adaptive Capacity of Healthcare Facilities for Air-Pollution Episodes in Dust-Storm-Prone Khuzestan, Iran: A Cross-Sectional Study

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39 **Abstract**

40 **Background:** Sand and dust storms can increase healthcare demand and disrupt service delivery, yet
41 evidence of facility-level preparedness in dust-prone health systems is limited. We assessed the
42 adaptive capacity for air-pollution episodes among hospitals and county health centres in Khuzestan
43 Province, Iran.

44 **Methods:** A cross-sectional census was conducted in 2024 across 52 units, comprising 24 county-level
45 health-network units and 28 hospitals. A 40-item checklist assessed seven adaptive-capacity domains
46 on a 0–100 scale. “Yes” responses were coded as 1, while “no” and “do not know” were coded as 0, as
47 the analytical dataset did not distinguish between them. Differences between hospitals and health
48 centres were estimated using Welch tests, 95% confidence intervals (CIs), Hedges’ g, permutation
49 tests, and false-discovery-rate (FDR) correction. Sensitivity analyses were performed, and managers’
50 preparedness and county social vulnerability were examined exploratorily. Dust was treated as a
51 regional hazard context because matched facility-level environmental measurements were unavailable.

52 **Results:** Hospitals scored higher than health centres for infrastructure and resources (72.0 [SD 24.5] vs
53 52.1 [23.7]; mean difference 19.9 points, 95% CI 6.5–33.4; Hedges’ g=0.81; FDR-adjusted p=0.031),
54 the only domain-level difference retained after FDR correction. The lowest mean scores overall were
55 for air-quality monitoring and evaluation (61.2), infrastructure and resources (62.8), and response and
56 recovery capacity (67.9). Only 30.8% used air-quality information to prioritise services, 36.5%
57 reported adequate equipment to receive affected patients, and 38.5% regularly received reliable air-
58 quality data. Hospital managers reported higher perceived preparedness than health-centre managers
59 (56.9 vs 47.2 on the 0–80 scale; mean difference 9.7, 95% CI 5.8–13.6; Hedges’ g=1.38; p<0.001).
60 Social-vulnerability associations were inconsistent, while the infrastructure difference remained
61 directionally consistent across sensitivity analyses.

62 **Conclusions:** Hospitals had stronger assessed infrastructure and higher manager-reported
63 preparedness, but system-wide gaps remained in air-quality intelligence, resources, and operational
64 response and evaluation. Findings support linking validated alerts to predefined facility actions,
65 resource mobilisation, continuity planning, and auditable performance indicators. Prospective studies
66 should determine whether assessed adaptive capacity translates into demonstrated resilience.

67 **Keywords:** adaptive capacity; air pollution; sand and dust storms; healthcare facilities; emergency
68 preparedness; hospitals; primary health care; perceived preparedness; social vulnerability; Khuzestan
69

70 **Background**

71 Sand and dust storms are recurrent environmental hazards in arid and semi-arid regions, increasingly
72 recognized as climate-sensitive contributors to particulate matter exposure and associated health risks
73 [1,2]. Dust plumes can traverse considerable distances, transporting complex mixtures of mineral
74 particles, chemical contaminants, microorganisms, and other biologically active constituents.
75 Epidemiological studies in Iran have linked exposure to desert dust and elevated particulate matter
76 with increased cardiorespiratory morbidity and mortality, while toxicological investigations in Ahvaz
77 have demonstrated the biological activity of locally collected particulate mixtures [3–8]. This body of
78 evidence collectively indicates a substantial population health burden. Nonetheless, the presence of
79 adverse health effects alone does not ascertain whether healthcare facilities are adequately
80 prepared to provide safe, timely, effective, and equitable services during recurrent dust and
81 severe air pollution episodes.

82 Health-system resilience is typically defined as the ability of a health system to anticipate, prepare for,
83 absorb, adapt to, and recover from disruptive events while maintaining essential functions [9].
84 Although adaptive capacity is a crucial component of resilience, it should not be equated with
85 demonstrated resilient performance during an actual emergency. In the context of dust storms and
86 severe air pollution, relevant institutional capacities include effective governance and accountability,
87 environmental surveillance and early-warning systems, staff training, risk communication, protective
88 infrastructure and air-filtration measures, continuity-of-operations and surge-capacity planning, and
89 formal coordination with environmental, meteorological, emergency-management, and municipal
90 authorities [10–12]. These capacities are critical in determining whether health facilities can translate
91 policy commitments into operational preparedness and continuity of care.

92 Evidence from dust-prone settings indicates that formal recognition of environmental hazards often
93 surpasses the level of operational implementation. Qualitative research in Iran has highlighted
94 fragmented organisational arrangements, inadequate risk assessment, weak intersectoral coordination,
95 and limited monitoring and evaluation of preparedness measures [13]. Similarly, a stakeholder survey
96 in the south-eastern Mediterranean revealed limited awareness of national dust-related policies and
97 inconsistent implementation of predefined protective plans [14]. A recent systematic review concluded
98 that effective mitigation in healthcare facilities necessitates an integrated approach encompassing risk
99 assessment, early warning, continuity planning, workforce preparation, protective infrastructure, and
100 intersectoral collaboration [15]. Broader reviews of climate-adaptive hospitals, health systems, and
101 primary-care services have identified similar priorities, particularly concerning surveillance,
102 infrastructure, workforce protection, governance, and continuity of essential services [16–21].

103 However, quantitative assessments comparing adaptive capacity across hospitals and primary
104 healthcare organisations within the same regional health system remain scarce.
105 Khuzestan Province in south-western Iran is affected by regional and transboundary dust, industrial
106 emissions, extreme heat, and substantial social and geographical vulnerability. Long-term monitoring
107 in Ahvaz, the provincial capital, has documented persistently elevated particulate pollution and
108 pollutant-specific temporal trends, providing local evidence of a sustained air-quality burden [22].
109 These overlapping hazards exert sustained pressure on healthcare organisations and underscore the
110 importance of facility-level preparedness and coordinated regional response. The parent Article 56
111 project identified the assessment of adaptive capacity and regional vulnerability as core objectives.
112 Accordingly, the present study addressed three questions: (1) how do seven domains of assessed
113 adaptive capacity differ between hospitals and county health centres; (2) which operational items
114 represent the most substantial preparedness gaps; and (3) whether facility-capacity patterns are
115 associated with county-level social vulnerability. Due to the unavailability of temporally and spatially
116 matched environmental measurements for individual facilities, dust exposure was considered as the
117 regional hazard context rather than a facility-specific exposure variable. Consequently, the study
118 evaluates organisational capacity within a dust-prone setting without estimating the effects of
119 measured dust exposure on individual facility performance.

120 **Methods**

121 *Study design and setting*

122 A cross-sectional study at the facility level was conducted in Khuzestan Province, located in south-
123 western Iran, during 2024. This study constituted the adaptive-capacity component of the Article 56
124 research project, titled “Assessing the Burden of Respiratory Disease Attributed to the Dust
125 Phenomenon in Khuzestan, with Emphasis on Building Resilience against Climate Change” (project
126 code: IR02-08-1402002112). Khuzestan frequently experiences dust storms and episodes of elevated
127 ambient particulate pollution, which provided the regional hazard context for the study. However, the
128 instruments employed assessed general organisational capacity and preparedness for air-pollution
129 episodes, rather than measuring actual service continuity, clinical performance, or operational
130 effectiveness during a specific dust event. The primary unit of analysis was the healthcare facility. The
131 study is reported in accordance with the Strengthening the Reporting of Observational Studies in
132 Epidemiology (STROBE) statement for cross-sectional studies [23], and statistical reporting adhered to
133 the SAMPL guidelines [24].

134 *Study population and facility frame*

135 The study employed a census approach to include all eligible healthcare organisational units within the
136 predefined project frame under Ahvaz Jundishapur University of Medical Sciences. The final
137 analytical frame comprised 52 independently assessed units: 28 hospitals and 24 county-level health-
138 network units.

139 The county-level health-network units should not be interpreted as individual frontline primary-care
140 clinics. Within the Iranian health system, each county is served by a health network that coordinates
141 and supervises primary healthcare services across its geographic area, typically through a county-level
142 health administration responsible for the network of subordinate health centres and other county-level
143 health-network units. Accordingly, the 24 health-network observations represented county-level
144 organisational and managerial units rather than individual community-based healthcare facilities.

145 The 24 health-network units corresponded to 23 operational health areas because East and West Ahvaz
146 were administered and assessed independently. For linkage with current county-level contextual
147 information, the study units were mapped to 22 current county contexts. Bandar Imam was treated as
148 an operational health area within Bandar Mahshahr County, while East and West Ahvaz were retained
149 as separate health-network observations in the primary facility-level analysis but were assigned to the
150 same Ahvaz county context for contextual analyses.

151 Because the eligible organisational frame was assessed as a census rather than sampled from a larger
152 population, no a priori sample-size calculation was performed. For each participating unit, a senior
153 manager, director, or designated official with direct knowledge of governance, resources,
154 infrastructure, emergency procedures, and routine operations served as the principal informant. All 52
155 eligible organisational units in the predefined study frame participated, with no exclusions.

156 *Data collection procedures*

157 Data collection was conducted in person by the research team members. Facility assessments were
158 accomplished through a combination of interviews with managers or other responsible personnel,
159 examination of available plans, records, administrative documents, and supporting evidence, as well as
160 direct observation when items could be assessed in this manner. A consistent questionnaire and
161 administration procedure were employed across all participating facilities. Documentary or
162 observational evidence was sought where applicable; however, the type and amount of supporting
163 documentation available varied among facilities and checklist items. Consequently, the findings are
164 characterized as assessed adaptive capacity or preparedness-related capacity, rather than independently
165 audited organizational performance.

166 *Primary adaptive-capacity instrument*

167 The research team developed a structured 40-item instrument to assess the adaptive capacity of
168 hospitals and county health centres to air-pollution and dust-related health emergencies. Items were
169 identified from relevant scientific, health-system, emergency-preparedness, and policy literature and
170 systematically organized into two sections.

171 The first section recorded facility characteristics, including county, institution name, and facility type.
172 The second section comprised 40 operational items organized into seven predefined domains: policies
173 and governance (7 items); infrastructure and resources (6 items); staff training and empowerment (5
174 items); air-quality monitoring and evaluation (6 items); public awareness and risk communication (6
175 items); response and recovery capacity (7 items); and intersectoral collaboration (3 items). These
176 domains were established through the instrument-development and content-validation process and
177 were treated analytically as content-defined operational groupings of items rather than as empirically
178 confirmed latent constructs; no latent-variable structure was assumed. Response options were “yes,”
179 “no,” and “do not know.”

180 *Instrument development and measurement properties*

181 Before field implementation, the content validity of the primary instrument was assessed by a panel of
182 six subject-matter experts, who evaluated the relevance, necessity, clarity, and comprehensiveness of
183 the proposed items. Content validity was quantified using established Content Validity Ratio (CVR)
184 and Content Validity Index (CVI) methods [25–27]. The overall CVR was 0.80 and the overall CVI
185 was 0.79, supporting acceptable content validity.

186 The instrument was subsequently pilot-tested with 20 respondents who were similar to the intended
187 study respondents. Internal consistency in the pilot sample was assessed using Cronbach’s alpha.
188 Domain-specific coefficients were 0.85 for policies and governance, 0.78 for infrastructure and
189 resources, 0.71 for staff training and empowerment, 0.83 for air-quality monitoring and evaluation,
190 0.71 for public awareness and risk communication, 0.81 for response and recovery capacity, and 0.66
191 for intersectoral collaboration. These estimates were considered preliminary indicators of internal
192 consistency rather than evidence of the dimensional structure of the instrument.

193 In the main study sample, Kuder–Richardson 20 (KR-20) coefficients were calculated as descriptive
194 measures of the internal consistency of the dichotomously scored item sets [28] and were reported
195 separately from the pilot Cronbach’s alpha estimates. Internal-consistency coefficients were not
196 interpreted as evidence that the predefined domains represented unidimensional latent constructs,
197 because such coefficients are influenced by the number of items, inter-item covariance, and

198 assumptions about measurement structure and do not, by themselves, establish structural or construct
199 validity [29–31].

200 No exploratory or confirmatory factor analysis was undertaken. The instrument was designed primarily
201 as an operational assessment checklist, and the sample of 52 facilities was not considered adequate for
202 stable estimation of the latent structure of a 40-item multidomain instrument. Accordingly, the seven
203 domains were interpreted as content-defined operational groupings for descriptive and comparative
204 analyses rather than as empirically confirmed latent constructs.

205 *Scoring of the Primary Instrument*

206 For analytical scoring, each affirmative response was assigned a value of 1. Responses of “no” and “do
207 not know” were treated as non-affirmative and assigned a value of 0. The analytical dataset did not
208 preserve distinct numerical codes for these two response categories; therefore, separate item-level
209 estimates for “no” and “do not know” responses could not be reported. This is an important limitation
210 because the analytical coding does not distinguish between an explicitly reported absence of capacity
211 and lack of knowledge or uncertainty about whether that capacity was present.

212 For each facility and domain, the normalized domain score was calculated as follows:

$$213 \quad \text{Domain score} = \frac{\text{Number of affirmative items}}{\text{Number of items in the domain}} \times 100$$

214 Domain scores ranged from 0 to 100, with higher scores indicating that a greater proportion of the
215 assessed operational capacities was reported as present. Normalization permitted comparison across
216 domains containing different numbers of items.

217 No validated or adequately documented prespecified cut-off was available for classifying domain
218 scores as favourable or unfavourable. A classification threshold used in an earlier analytical version
219 could not be verified from the available study documentation and was therefore **not retained** in the
220 final analysis. No post hoc threshold was introduced. Accordingly, the seven normalized domain
221 scores were analysed as continuous operational summary measures and constituted the primary
222 outcomes.

223 For each facility, an overall item-weighted percentage was also calculated by dividing the total number
224 of affirmative responses across all 40 items by 40 and multiplying by 100. This exploratory summary
225 assigned equal weight to each individual item rather than equal weight to each domain. It was used
226 only for descriptive facility profiling and was not interpreted as a validated overall adaptive-capacity or
227 resilience scale, nor did it replace the domain-specific analyses.

228 *Managers' perceived-preparedness instrument*

229 A second researcher-developed instrument assessed managers' perceptions of their facility's
230 preparedness to mitigate air-pollution exposure and manage associated health impacts. It comprised a
231 demographic and professional-information section and 20 statements assessing perceived
232 preparedness.

233 Items were rated on a five-point Likert scale from "strongly disagree" to "strongly agree" and coded
234 from 0 to 4 for analysis. Item scores were summed to produce a total score ranging from 0 to 80, with
235 higher scores indicating greater perceived preparedness. No items were reverse scored.

236 Before field implementation, the instrument was reviewed by seven subject-matter experts. Archived
237 instrument-development records reported an overall Content Validity Ratio (CVR) of 0.89 and an
238 overall Content Validity Index (CVI) of 0.85. Because the available records did not document the
239 method used to aggregate item-level CVR and CVI values, these coefficients are reported descriptively
240 as recorded in the original validation documentation. Pilot testing with 20 managers similar to the
241 intended respondents yielded a total-scale Cronbach's alpha of 0.91, providing preliminary evidence of
242 internal consistency.

243 The perceived-preparedness score was treated as a secondary, exploratory measure. Associations with
244 the seven adaptive-capacity domain scores were interpreted cautiously because both instruments
245 obtained information from facility management, creating potential common-source or common-method
246 variance [32]. The resulting correlations were therefore not interpreted as independent evidence of
247 construct or convergent validity or as indicating causal relationships.

248 Item-level responses to this instrument were not available in the revision-stage analytical archive.
249 Analyses were therefore restricted to verified facility-type aggregate statistics and archived domain-
250 level correlations; no additional item-level or multivariable analyses were undertaken.

251 *Contextual literature searches and source appraisal*

252 A targeted contextual evidence search was undertaken to identify social, demographic, deprivation,
253 dust, particulate-pollution, and other environmental information relevant to interpretation of the
254 facility-level findings. This activity was intended to support source identification and selection of
255 contextual variables and was not designed or reported as a systematic review.

256 Searches covered PubMed, Scopus, Iranian scientific repositories, official statistical and government
257 sources, and relevant grey literature. Scite was used only as an auxiliary discovery and citation-context
258 tool to identify potentially relevant publications and examine how selected references had been cited.

259 Candidate references identified through Scite or other automated search tools were verified against the
260 original publication, bibliographic database records, and DOI metadata before inclusion.
261 The search strategy was purposive rather than systematic and prioritized sources capable of providing
262 county-level or otherwise geographically relevant contextual information. Search concepts included
263 combinations of terms relating to social vulnerability, deprivation, socioeconomic development, food
264 insecurity, dust days, sand and dust storms, air pollution, particulate matter, Khuzestan, and Iran.
265 For each potentially relevant source, the research team documented the publication and data-collection
266 years; geographic coverage and spatial unit; indicator definitions; underlying data sources; index-
267 construction or weighting methods, where applicable; direction and interpretation of the measure;
268 relevance to the present study; proposed analytical role; and important temporal, geographic, or
269 conceptual limitations.
270 Initial source extraction and classification were independently checked by a second team member.
271 Disagreements concerning source interpretation, geographic linkage, or analytical use were resolved
272 by re-examining the original source and reaching consensus within the research team. The complete
273 source inventory, extracted variables, appraisal decisions, and documentation of their intended
274 analytical roles are provided in the supplementary materials.

275 *County-level social vulnerability*

276 County-level social vulnerability was represented using the previously published Khuzestan social-
277 vulnerability index developed by Arvin et al. [33]. The index incorporated 19 demographic,
278 socioeconomic, educational, housing, and social-protection indicators derived from the 2016 national
279 census, the 2017 Khuzestan Statistical Yearbook, and provincial socioeconomic reports covering
280 2016–2017. Higher values of the published Q index indicated greater social vulnerability.
281 The present study did not reconstruct, reweight, or otherwise modify the published index. Each facility
282 was assigned the Q value corresponding to its county. East and West Ahvaz were assigned the same
283 Ahvaz value, and the Bandar Imam operational area was assigned the Bandar Mahshahr value.
284 Because the historical source did not report separate values for the subsequently established counties of
285 Karkheh and Dezpart, values from their respective parent counties were assigned as explicitly flagged
286 geographic proxies. To assess the influence of these proxy assignments, contextual analyses were
287 repeated after excluding facilities located in the affected counties.
288 Other deprivation, food-insecurity, health-development, and rural-development measures identified
289 through the contextual evidence search were not combined with the Q index. Measures incorporating
290 health-service resources, healthcare infrastructure, or closely related service-capacity indicators were

not used as primary contextual covariates because of their conceptual overlap with the facility adaptive-capacity outcomes and the resulting risk of circular interpretation. Alternative contextual measures were retained only for descriptive appraisal or sensitivity analyses where appropriate.

Environmental context

Environmental information on dust-event frequency, PM₁₀, PM_{2.5} visibility, monitoring-station characteristics, and related indicators was appraised separately from the county-level social-vulnerability analysis. Available environmental sources showed substantial heterogeneity in observation periods, pollutant definitions, monitoring coverage, spatial resolution, and geographic scope. Several estimates were limited to Ahvaz or other individual cities, and no identified source provided temporally aligned, spatially comparable 2024 environmental exposure estimates covering all 52 study facilities.

Accordingly, historical or city-specific environmental estimates were not extrapolated to facilities outside their documented geographic coverage. Dust-event frequency and particulate-matter concentrations were not incorporated into the published Q social-vulnerability index and were not entered as facility-level covariates in the primary regression or comparative analyses. Instead, the environmental evidence was used to characterize the broader provincial hazard context in which the facilities operated.

Facility locations and descriptive mapping

Facility coordinates were compiled from institutional and geographic sources and stored using the World Geodetic System 1984 (WGS 84) geographic coordinate reference system. The spatial database retained information on coordinate provenance and confidence to support traceability of facility locations.

A province-wide point map was produced to describe the geographic distribution of hospitals and county health centres across Khuzestan. The map was intended for descriptive visualization only and was not used to infer facility accessibility, service catchments, referral relationships, or environmental exposure.

Accessibility analysis, referral-network modelling, two-step floating catchment area methods, and dust-related travel-time modelling were beyond the scope of the present study.

Data quality assurance and analytical dataset

The analytical dataset contained one record for each independently assessed facility, linked to a unique and stable facility identifier. Before statistical analysis, a structured data-quality audit was undertaken. Checks included confirmation of the final facility frame and facility type; verification of the

323 uniqueness of facility identifiers and names; assessment of item-value ranges and missingness;
324 reconstruction of domain totals from item-level responses; comparison of reconstructed and stored
325 domain totals; identification of identical 40-item response profiles; and verification of geographic and
326 contextual linkage fields.

327 One out-of-range value of 11 was identified in an item expected to contain binary analytical values.
328 Following verification against the binary coding structure and the corresponding corrected domain
329 total, the value was corrected to 1. The affected field, correction, rationale, and date of correction were
330 documented in the audit log. After this correction, all item values were within the expected range, no
331 item-level values were missing, and no statistical imputation was required.

332 Six stored facility-domain totals differed from totals reconstructed directly from the 40 item-level
333 responses. Because the item-level data represented the most granular reproducible source available for
334 analysis, domain scores reconstructed from these responses were used in the primary analyses.
335 Analyses using the corrected stored aggregate domain totals were conducted separately as sensitivity
336 analyses to assess whether these discrepancies materially affected the findings.

337 Four groups of facilities had identical response profiles across all 40 items. These records were
338 retained because they corresponded to separately identified facilities that had been independently
339 assessed. Identical response patterns were therefore documented as a data-quality finding rather than
340 treated as sufficient grounds for record deletion. Such patterns may reflect genuinely standardized
341 practices across facilities or possible duplication in reporting; the available data did not permit these
342 explanations to be distinguished.

343 The finalized analytical dataset, variable dictionary, correction log, geographic and contextual
344 crosswalks, analytical code, and statistical outputs were versioned and preserved as components of the
345 study audit trail.

346 *Statistical analysis*

347 Continuous domain scores were summarized using the mean, standard deviation (SD), median,
348 interquartile range (IQR), minimum, and maximum. Item-level affirmative responses were
349 summarized as counts and percentages.

350 The primary comparative analysis examined differences between hospitals (n=28) and county health
351 centres (n=24) across the seven normalized adaptive-capacity domain scores. For each domain, the
352 principal effect estimate was the mean difference in percentage points, calculated as the hospital mean
353 minus the health-centre mean, with a corresponding 95% confidence interval (CI). Thus, positive
354 values indicated higher mean assessed adaptive capacity among hospitals. Because the study was

cross-sectional and facility type was not randomly assigned, these comparisons were interpreted as descriptive comparative associations and not as causal effects.

Welch's two-sample t-test was used for the primary between-group comparisons because it does not require equality of group variances and provides greater robustness than the conventional pooled-variance t-test when variances differ [34]. Confidence intervals were calculated using Welch-Satterthwaite degrees of freedom. Standardized between-group differences were additionally expressed as Hedges' g, incorporating the small-sample bias correction [35]. Hedges' g was reported as a point estimate of standardized effect magnitude; uncertainty for the primary group contrast was represented by the 95% CI for the unstandardized mean difference, supplemented by the bootstrap interval.

To assess the robustness of the estimated mean differences and their confidence intervals, a stratified non-parametric bootstrap was performed [36]. Facilities were sampled with replacement separately within the hospital and health-centre groups, preserving the observed group sizes of 28 and 24, respectively. The hospital-minus-health-centre mean difference was recalculated for each bootstrap sample. A total of 10,000 bootstrap replications was performed for each domain, and percentile-based 95% CIs were defined by the 2.5th and 97.5th percentiles of the bootstrap distribution. These bootstrap estimates were used as robustness analyses rather than as replacements for the primary Welch-based estimates. Percentile intervals were selected for their direct interpretability, while recognizing that they may have less favourable coverage properties than bias-corrected and accelerated intervals in markedly skewed distributions.

Two-sided permutation tests were also conducted as distribution-free robustness analyses. Facility-type labels were randomly reassigned across the 52 observed facility-level score profiles while preserving the original numbers of hospitals and health centres. For each domain, the test statistic was the hospital-minus-health-centre difference in mean scores. A total of 50,000 random permutations was generated. The two-sided Monte Carlo permutation p-value was calculated using the add-one correction [37]:

$$p_{\text{perm}} = \frac{1 + \sum_{b=1}^B I(|T_b| \geq |T_{\text{obs}}|)}{B + 1}$$

where T_{obs} denotes the observed difference in group means, T_b denotes the corresponding difference from the b th permutation, $B=50,000$, and $I(\cdot)$ is the indicator function. The add-one correction provides a finite-simulation estimate and avoids reporting a Monte Carlo p-value of zero. Bootstrap and permutation procedures were implemented using a prespecified random seed (20260803) to support computational reproducibility.

386 To account for multiple testing across the seven primary domain-level comparisons, the Benjamini–
387 Hochberg procedure was applied to control the false discovery rate (FDR) [38]. Both unadjusted and
388 FDR-adjusted p-values were reported. Statistical interpretation emphasized effect estimates and 95%
389 CIs alongside p-values rather than statistical significance alone.

390 For each of the 40 operational items, the proportion of affirmative responses was compared between
391 hospitals and health centres using two-sided Fisher’s exact tests. Item-level effect estimates included
392 the absolute percentage-point difference in affirmative responses and the odds ratio (OR), each
393 accompanied by a 95% CI where applicable. When a two-by-two table contained a zero cell, 0.5 was
394 added to all four cells solely for estimation of the OR and its CI; Fisher’s exact p-values were
395 calculated from the original, uncorrected contingency tables. The Benjamini–Hochberg procedure was
396 applied separately across the family of 40 item-level comparisons. These item-level analyses were
397 considered exploratory because of the large number of comparisons and limited statistical power.

398 **Sensitivity Analyses**

399 Three primary sensitivity analyses were undertaken. Initially, East and West Ahvaz were combined by
400 averaging their normalized domain scores, resulting in 51 administrative analytical units. The principal
401 facility-type effect estimates were recalculated and compared with those from the primary analysis
402 (N=52). Subsequently, facility-type comparisons were repeated using the corrected aggregate domain
403 totals instead of the item-derived scores. Finally, a geographically paired analysis was conducted for
404 21 operational areas, each containing both a hospital and a county health centre. Differences between
405 hospitals and health centres were calculated within these operational areas. A paired sign-permutation
406 test was performed by randomly reversing the signs of the within-area differences and recalculating the
407 mean paired difference, utilizing a total of 50,000 random sign allocations. The exploratory overall
408 item-weighted percentage was analyzed separately and did not replace the seven domain-specific
409 outcomes.

410 **Contextual Statistical Analyses**

411 Because social vulnerability was measured at the county level, the primary contextual analysis aligned
412 the contextual exposure and adaptive-capacity outcomes at the same geographic level to avoid treating
413 facilities sharing an identical county-level vulnerability value as independent contextual observations.
414 Facility domain scores were therefore aggregated within current county and facility type, and
415 Spearman rank correlations between the continuous social-vulnerability Q index and each of the seven
416 domain scores were estimated separately for hospitals and health centres. Confidence intervals were
417 obtained by resampling geographic units rather than individual facilities. Multiplicity adjustment was

418 applied across the seven domain-specific correlations within each facility-type analysis. Given the
419 small number of current county contexts represented (n=22), these analyses were considered
420 exploratory and were interpreted cautiously, with emphasis on the direction, magnitude, and
421 consistency of associations rather than statistical significance alone.

422 As a complementary secondary analysis, facility-level linear regression models were fitted for each
423 domain score with facility type and the continuous Q index as predictors. Because facilities within the
424 same county shared the same contextual vulnerability value and could have correlated outcomes,
425 standard errors were clustered by current county using a finite-sample-corrected cluster-robust
426 covariance estimator [39]. With only 22 county clusters, estimates from these models were regarded as
427 exploratory and were not used to support strong inferential or causal conclusions.

428 Sensitivity analyses repeated the contextual models after excluding facilities in Karkheh and Dezpart,
429 for which parent-county vulnerability values had been assigned as geographic proxies, and separately
430 after excluding Ahvaz because of its comparatively large and distinctive urban context. No stepwise
431 variable-selection procedures or high-dimensional covariate adjustment were undertaken. Facility-
432 type-by-vulnerability interaction terms were also not fitted because the limited number of geographic
433 units provided insufficient information for reliable estimation of differential vulnerability associations
434 by facility type.

435 *Computational environment and reproducibility*

436 All analyses involving study data were conducted internally on a secure local computer system. The
437 primary analytical workflow employed Python version 3.13.9 via the Anaconda distribution, utilizing
438 conda version 25.11.1. Code development occurred in Visual Studio Code and was maintained under
439 Git version control. The principal Python packages included NumPy, SciPy, and statsmodels. Selected
440 calculations and outputs underwent independent verification using R for Windows version 4.6.0. All
441 variable definitions, coding rules, data corrections, score-construction procedures, geographic
442 crosswalks, exclusions, resampling procedures, and sensitivity analyses were documented in audit files
443 and executable code. All stochastic procedures utilized a pseudorandom-number generator initialized
444 with the fixed seed 20260803. The seed, resampling unit, stratification or pairing structure, number of
445 replications, and resulting estimates were documented in the analytical code.

446 *Use of automated and artificial-intelligence-assisted tools*

447 Scite was used for literature discovery and citation-context assessment. References identified using
448 Scite were verified against original publications and bibliographic and DOI metadata before inclusion.

449 OpenAI GPT-based tools assisted with analytical-code refinement, debugging, troubleshooting, and
450 documentation. Generative AI-assisted tools were used for language editing, manuscript organization,
451 and visual-layout support. Outputs were treated as suggestions, reviewed, revised, and verified by the
452 authors. Final statistical analyses were conducted by the team using secured analytical data and
453 verified procedures.

454 AI-assisted tools did not make decisions regarding the research question, study design, analytical
455 approach, interpretation, or result selection. These decisions remained with the authors. AI-generated
456 or AI-assisted code, descriptions, references, tables, figures, and manuscript text were reviewed before
457 inclusion. AI tools were not authors. The authors take responsibility for the manuscript.

458 *Ethics approval and consent to participate*

459 The Ethics Committee of Ahvaz Jundishapur University of Medical Sciences
460 (IR.AJUMS.REC.1402.190) granted approval for the study. Participants were provided with written
461 information detailing the study's objectives, the voluntary nature of participation, confidentiality
462 measures, and the reporting of findings in aggregate form. Prior to participation, written informed
463 consent was obtained from all participants.

464

465 **Results**

466 **Facility inclusion, geographic coverage, and data quality**

467 All 52 eligible facilities in the predefined study frame participated and were included in the analysis,
468 comprising 24 county-level health-network units and 28 hospitals. No eligible facility was excluded.
469 Following data-quality correction, item-level completeness was 100%, with no missing responses
470 across the 40 operational items.

471 The facilities represented 23 operational health areas corresponding to 22 current county contexts.
472 Ahvaz contained the largest number of assessed facilities, comprising seven hospitals and two
473 independently assessed health-centre units. Bandar Mahshahr County included two hospitals and two
474 health-centre units distributed across the Mahshahr and Bandar Imam operational areas. East and West
475 Ahvaz were retained as separate independently assessed health-centre units in the primary facility-level
476 analysis but were linked to the same Ahvaz county context for county-level analyses. The geographic
477 distribution of the study facilities is shown in Figure 1.

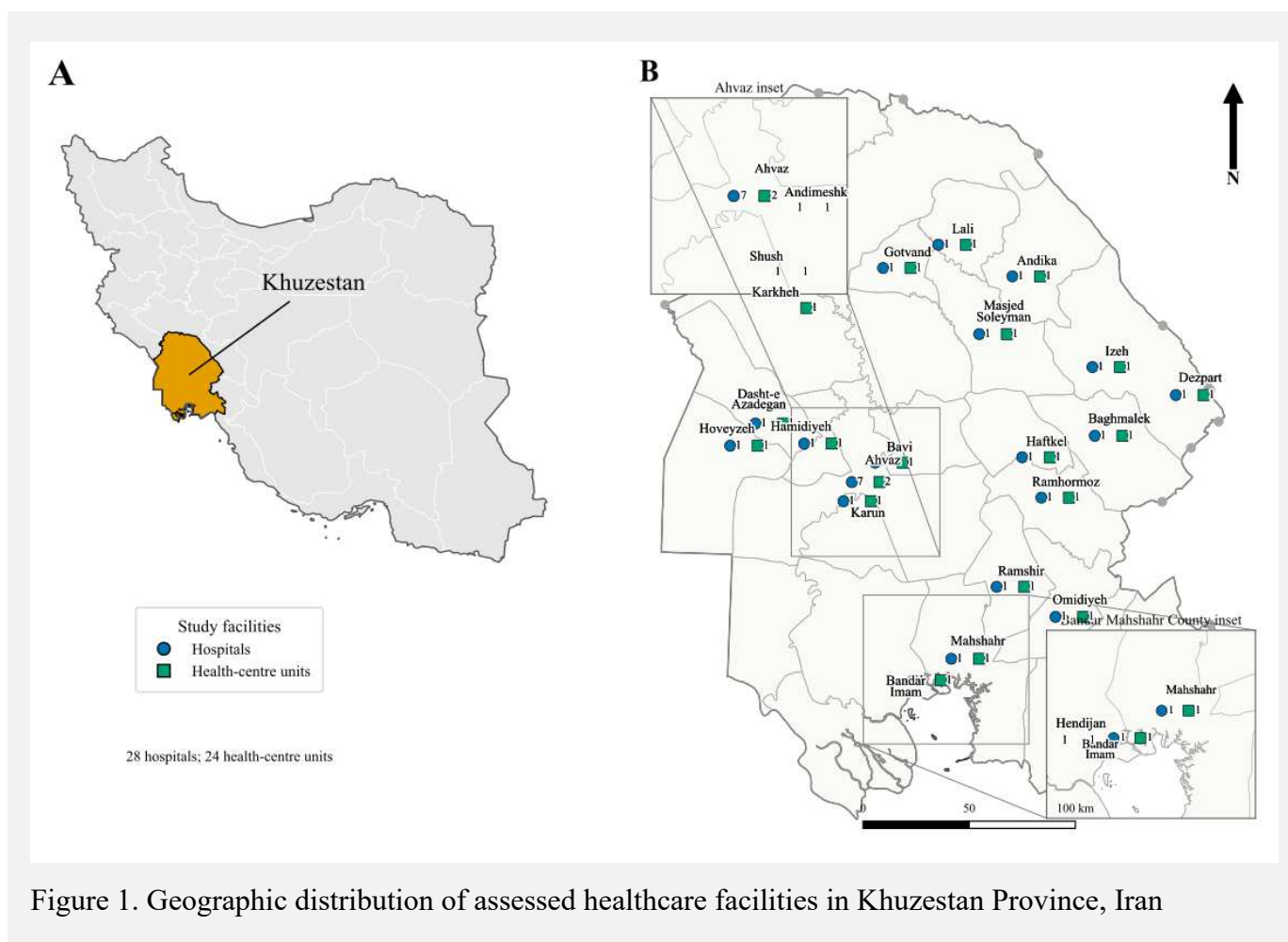


Figure 1. Geographic distribution of assessed healthcare facilities in Khuzestan Province, Iran

The data-quality audit identified one out-of-range value of 11 in an item expected to contain binary analytical values. Following verification against the item coding structure and the corresponding corrected domain total, the value was corrected to 1 before calculation of the analytical scores. No missing or out-of-range item values remained after this correction.

Four groups of facilities had identical response profiles across all 40 operational items. These observations were retained because they represented separately identified and independently assessed facilities; identical response patterns were documented as a data-quality finding rather than treated as evidence of duplicate records.

486 Six stored facility-domain totals differed from totals reconstructed directly from the underlying item
487 responses. Because the item-level responses constituted the most granular and reproducible analytical
488 source, item-derived domain scores were used for the primary analyses. Analyses using the corrected
489 aggregate domain totals were conducted separately as sensitivity analyses.

490 **Adaptive-capacity domain scores and facility-type comparisons**

491 Across all facilities, the highest mean domain scores were observed for staff training and
492 empowerment (87.7, SD 20.3), intersectoral collaboration (82.7, SD 21.4), and public awareness and
493 risk communication (77.9, SD 20.5). The lowest mean scores were observed for air-quality monitoring
494 and evaluation (61.2, SD 24.4), infrastructure and resources (62.8, SD 25.9), and response and
495 recovery capacity (67.9, SD 25.1).

496 Hospitals had higher mean scores than health centres in six of the seven domains (Table 1; Figure 2).
497 The largest between-group difference was observed for infrastructure and resources: hospitals had a
498 mean score of 72.0 (SD 24.5), compared with 52.1 (SD 23.7) among health centres. The hospital-
499 minus-health-centre mean difference was 19.9 percentage points (95% CI 6.5 to 33.4), with a
500 standardized effect size of Hedges' $g=0.81$. This was the only domain-level comparison that remained
501 statistically significant after FDR adjustment across the seven domains (Welch $p=0.004$; FDR-adjusted
502 $p=0.031$). Robustness analyses yielded concordant findings: the percentile bootstrap 95% CI was 7.5 to
503 33.0 percentage points, and the two-sided permutation p value was 0.005. The direction and
504 approximate magnitude of the infrastructure difference were also maintained across the prespecified
505 sensitivity analyses.

506 For response and recovery capacity, hospitals scored on average 13.3 percentage points higher than
507 health centres (95% CI -0.3 to 26.9; Hedges' $g=0.53$; Welch $p=0.056$; FDR-adjusted $p=0.195$). The
508 percentile bootstrap 95% CI ranged from 0.3 to 26.6 points, whereas the permutation p value was
509 0.061. Thus, although the point estimates consistently favoured hospitals, inferential evidence varied
510 across analytical approaches, and the comparison did not remain statistically significant after
511 adjustment for multiple testing. This finding was therefore interpreted as suggestive rather than
512 conclusive.

513 Intersectoral collaboration was the only domain in which hospitals had a lower mean score than health
514 centres: 79.8 (SD 24.6) versus 86.1 (SD 16.8), respectively. The mean difference was -6.3 percentage
515 points (95% CI -18.0 to 5.3; Hedges' $g=-0.29$; FDR-adjusted $p=0.359$). For all other domain
516 comparisons, the 95% CIs for the hospital-minus-health-centre mean differences included zero, and
517 none remained statistically significant after FDR adjustment.

518 **Table 1. Adaptive-capacity domain scores and hospital–health-centre comparisons**

519 **Panel A. Descriptive statistics**

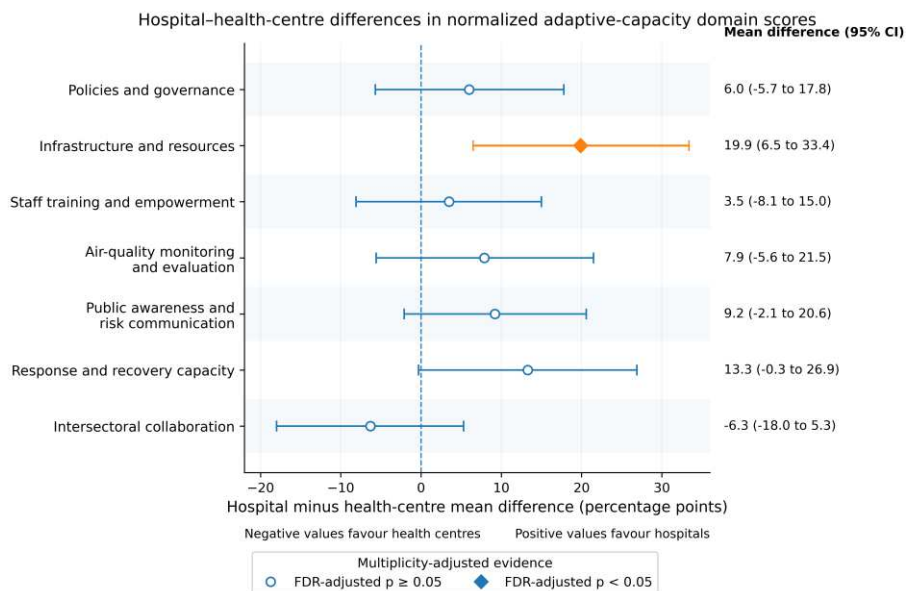
Domain	All facilities mean (SD)	All facilities median (IQR)	Health centres mean (SD)	Hospitals mean (SD)
Policies and governance	71.7 (21.6)	71.4 (57.1–85.7)	68.5 (17.4)	74.5 (24.7)
Infrastructure and resources	62.8 (25.9)	66.7 (50.0–70.8)	52.1 (23.7)	72.0 (24.5)
Staff training and empowerment	87.7 (20.3)	100.0 (80.0–100.0)	85.8 (22.4)	89.3 (18.4)
Air-quality monitoring and evaluation	61.2 (24.4)	66.7 (50.0–70.8)	56.9 (23.5)	64.9 (25.0)
Public awareness and risk communication	77.9 (20.5)	83.3 (66.7–100.0)	72.9 (20.7)	82.1 (19.7)
Response and recovery capacity	67.9 (25.1)	71.4 (53.6–85.7)	60.7 (23.5)	74.0 (25.2)
Intersectoral collaboration	82.7 (21.4)	100.0 (66.7–100.0)	86.1 (16.8)	79.8 (24.6)

520 **Panel B. Effect estimates and robustness analyses**

Domain	Mean difference (95% CI)	Hedges' <i>g</i>	Welch <i>p</i>	FDR <i>p</i>	Bootstrap 95% CI	Permutation <i>p</i>
Policies and governance	6.0 (−5.7 to 17.8)	0.27	0.308	0.359	−5.5 to 17.0	0.368
Infrastructure and resources	19.9 (6.5 to 33.4)	0.81	0.004	0.031	7.5 to 33.0	0.005
Staff training and empowerment	3.5 (−8.1 to 15.0)	0.17	0.552	0.552	−7.5 to 14.4	0.596
Air-quality monitoring and evaluation	7.9 (−5.6 to 21.5)	0.32	0.244	0.359	−5.1 to 20.8	0.254
Public awareness and risk communication	9.2 (−2.1 to 20.6)	0.45	0.109	0.253	−1.7 to 19.7	0.115
Response and recovery capacity	13.3 (−0.3 to 26.9)	0.53	0.056	0.195	0.3 to 26.6	0.061
Intersectoral collaboration	−6.3 (−18.0 to 5.3)	−0.29	0.277	0.359	−18.1 to 4.6	0.389

521

522 Scores range from 0 to 100. Mean differences are calculated as hospital minus health-centre means and are expressed in
523 percentage points. Hedges' *g* is reported as a standardized effect-size point estimate; uncertainty is represented primarily
524 by the 95% CI for the unstandardized mean difference and by the bootstrap 95% CI. FDR *p* values were calculated using
525 the Benjamini–Hochberg procedure across the seven domain comparisons. Bootstrap intervals are percentile intervals
526 based on 10,000 stratified resamples. Permutation *p* values are based on 50,000 random reallocations using the
527 prespecified seed 20260803.



528

Scores range from 0 to 100. Horizontal bars show Welch 95% confidence intervals. FDR adjustment used the Benjamini–Hochberg procedure across seven domains.

529 **Figure 2. Hospital–health-centre differences in normalized adaptive-capacity domain scores.** Points represent
530 hospital-minus-health-centre mean differences in percentage points, and horizontal bars represent 95% confidence

531 intervals calculated using the Welch–Satterthwaite method. Positive values indicate higher mean scores in hospitals;
 532 negative values indicate higher mean scores in health centres.

533 Main-sample internal consistency

534 The KR-20 coefficients specific to each domain varied, with a range from 0.308 for intersectoral
 535 collaboration to 0.657 for response and recovery capacity. The overall coefficient for the combined 40
 536 items was 0.883, as shown in Table 2. These coefficients were considered as descriptive characteristics
 537 of the predefined operational item groups and were not used to infer unidimensionality.

538 **Table 2. Main-sample internal-consistency coefficients**

<i>Scale or domain</i>	<i>Number of items</i>	<i>KR-20</i>
<i>Policies and governance</i>	7	0.526
<i>Infrastructure and resources</i>	6	0.584
<i>Staff training and empowerment</i>	5	0.650
<i>Air-quality monitoring and evaluation</i>	6	0.554
<i>Public awareness and risk communication</i>	6	0.549
<i>Response and recovery capacity</i>	7	0.657
<i>Intersectoral collaboration</i>	3	0.308
<i>All 40 items</i>	40	0.883

539 *KR-20 is reported descriptively for binary item sets. The 40-item coefficient does not imply that the checklist*
 540 *represents a single latent construct.*

541 Managers’ perceived preparedness

542 Hospital managers exhibited a higher mean perceived-preparedness score compared to health-centre
 543 managers. On a scale of 0 to 80, the mean score was 56.9 (SD 6.8) for 28 hospital managers, whereas it
 544 was 47.2 (SD 7.1) for 24 health-centre managers. The mean difference between hospital and health-
 545 centre managers was 9.7 points (95% CI 5.8 to 13.6; Welch $t=5.01$, $df=48.1$; $p<0.001$), with a
 546 corresponding Hedges’ g of 1.38.

547 All seven correlations between managers’ perceived-preparedness scores and the assessed adaptive-
 548 capacity domains were positive (Table 3). The strongest correlations were identified for infrastructure
 549 and resources ($r=0.71$, 95% CI 0.54 to 0.82), response and recovery capacity ($r=0.69$, 95% CI 0.51 to
 550 0.81), and air-quality monitoring and evaluation ($r=0.65$, 95% CI 0.46 to 0.78). The correlations for the
 551 remaining domains ranged from 0.47 to 0.63. These associations were interpreted with caution, as both
 552 measures were derived from the same organisational assessment context.

553 **Table 3. Managers’ perceived preparedness and its association with adaptive-capacity domains**

554 Panel A. Facility-type comparison

<i>Group or estimate</i>	<i>n</i>	<i>Mean (SD)</i>	<i>Estimate</i>
<i>Health-centre managers</i>	24	47.2 (7.1)	—
<i>Hospital managers</i>	28	56.9 (6.8)	—
<i>Hospital minus health centre</i>	52	—	9.7 (95% CI 5.8 to 13.6); $g=1.38$; $p<0.001$

555 Panel B. Domain correlations

<i>Domain</i>	<i>Mean domain score</i>	<i>Correlation r</i>	<i>95% CI</i>
<i>Policies and governance</i>	71.7	0.63	0.431 to 0.770
<i>Infrastructure and resources</i>	62.8	0.71	0.542 to 0.823
<i>Staff training and empowerment</i>	87.7	0.58	0.365 to 0.736
<i>Air-quality monitoring and evaluation</i>	61.2	0.65	0.458 to 0.784
<i>Public awareness and risk communication</i>	77.9	0.53	0.301 to 0.701
<i>Response and recovery capacity</i>	67.9	0.69	0.514 to 0.810
<i>Intersectoral collaboration</i>	82.7	0.47	0.226 to 0.658

Domain scores are normalized 0–100 checklist scores. Correlation confidence intervals were calculated using Fisher's z transformation. Correlations are descriptive and do not establish independent criterion validity or causal pathways.

Operational item findings

The capacity least frequently reported was the utilization of air-quality data to establish priorities for service provision, as indicated by 16 out of 52 facilities (30.8%). Other commonly identified deficiencies included the lack of adequate equipment for treating patients with conditions caused or worsened by air pollution (19/52, 36.5%), the irregular receipt of air-quality data from reliable sources (20/52, 38.5%), insufficient resources for maintaining services during air-pollution emergencies (22/52, 42.3%), the absence of programmes for the timely dissemination of air-quality information (22/52, 42.3%), and the use of air-quality data to assess the effectiveness of responses (24/52, 46.2%). Significant unadjusted differences between hospitals and health centers were noted in the regular updating of air-pollution-related policies (71.4% versus 29.2%), the availability of equipment and technologies necessary for managing air-pollution-related illnesses (92.9% versus 58.3%), and the reallocation of resources and equipment during severe air pollution events (85.7% versus 50.0%). The corresponding Fisher exact p-values were 0.005, 0.007, and 0.007, respectively. However, none of the 40 item-level comparisons remained statistically significant after FDR correction, with an adjusted p value of 0.098 for each of these three comparisons (Table 4).

Table 4. Principal operational gaps and largest unadjusted item-level differences

Panel A. Lowest affirmative-response proportions

<i>Item</i>	<i>Domain</i>	<i>Operational indicator</i>	<i>Affirmative n/N (%)</i>
20	Air-quality monitoring and evaluation	The facility uses air-quality data to set priorities for service provision.	16/52 (30.8%)
9	Infrastructure and resources	The facility is adequately equipped to receive patients with illnesses caused or exacerbated by air pollution.	19/52 (36.5%)
19	Air-quality monitoring and evaluation	The facility regularly receives air-quality data from reliable sources.	20/52 (38.5%)
13	Infrastructure and resources	The facility has sufficient resources to provide services during air-pollution emergencies.	22/52 (42.3%)
30	Public awareness and risk communication	The facility has programmes for timely dissemination of air-quality information.	22/52 (42.3%)

37 | Response and recovery capacity | The facility uses air-quality data to evaluate response effectiveness. | 24/52 (46.2%)

576 **Panel B. Smallest unadjusted Fisher exact p values**

Item	Operational indicator	Health centres n/N (%)	Hospitals n/N (%)	Difference, points	Fisher p	FDR p
2	The facility regularly updates health policies related to air pollution.	7/24 (29.2%)	20/28 (71.4%)	42.3	0.005	0.098
8	The facility has equipment and technologies required to manage air-pollution-related illnesses.	14/24 (58.3%)	26/28 (92.9%)	34.5	0.007	0.098
33	The facility reallocates resources and equipment during severe air pollution.	12/24 (50.0%)	24/28 (85.7%)	35.7	0.007	0.098

577 *Differences are hospital minus health-centre affirmative-response percentages. Item-level FDR adjustment was*
578 *applied across all 40 comparisons.*

579 Sensitivity analyses

580 The estimated hospital–health-centre difference in infrastructure and resources remained similar in
581 magnitude across all three prespecified sensitivity analyses. After combining East and West Ahvaz, the
582 mean difference was 20.6 percentage points (FDR-adjusted p=0.029). Using the corrected stored
583 domain totals, the corresponding difference was 19.2 points (FDR-adjusted p=0.051). In the analysis
584 restricted to 21 geographically paired operational areas, the mean within-area difference was 16.7
585 points (95% CI 2.9 to 30.4; paired p=0.020); however, after adjustment across the seven paired domain
586 comparisons, the FDR-adjusted p value was 0.142. Thus, although multiplicity-adjusted statistical
587 significance was not retained in every sensitivity analysis, the direction and approximate magnitude of
588 the infrastructure difference were consistently maintained.

589 For response and recovery capacity, hospital–health-centre differences also remained positive across
590 the sensitivity analyses, ranging from 10.9 to 14.4 percentage points. None of these comparisons
591 remained statistically significant after adjustment across the seven domains. Aggregation of East and
592 West Ahvaz and use of the corrected stored domain totals preserved the direction of all seven primary
593 domain estimates. In the geographically paired analysis, however, the estimate for intersectoral
594 collaboration moved substantially toward the null, from –6.3 points in the primary analysis to 1.6
595 points. The results of the three prespecified sensitivity analyses are summarised in Table 5.

596 **Table 5. Sensitivity-analysis summary**

Domain	Primary diff.	Primary FDR p	Ahvaz combined diff.	FDR p	Corrected totals diff.	FDR p	Paired- area diff.	Paired FDR p
Policies and governance	6.0	0.359	7.4	0.289	7.6	0.281	2.0	0.748
Infrastructure and resources	19.9	0.031	20.6	0.029	19.2	0.051	16.7	0.142

Staff training and empowerment	3.5	0.552	4.1	0.493	3.5	0.552	1.9	0.748
Air-quality monitoring and evaluation	7.9	0.359	9.8	0.252	6.6	0.391	4.8	0.643
Public awareness and risk communication	9.2	0.253	10.4	0.168	10.5	0.145	6.3	0.379
Response and recovery capacity	13.3	0.195	14.4	0.143	13.3	0.145	10.9	0.187
Intersectoral collaboration	-6.3	0.359	-5.7	0.384	-6.3	0.388	1.6	0.748

Differences are hospital minus health-centre scores in percentage points. The Ahvaz-combined analysis contained 51 administrative analytical units. The paired analysis included 21 operational areas with one hospital and one health-centre observation.

County-level social vulnerability

County-level analyses did not show a consistent monotonic association between social vulnerability and the seven adaptive-capacity domains. Among the 22 county-level health-centre summaries, Spearman correlation coefficients ranged from -0.259 to 0.202. Among the 21 county-level hospital summaries, coefficients ranged from -0.105 to 0.331. All unadjusted p values were ≥ 0.143 , and none of the correlations remained statistically significant after FDR adjustment.

In exploratory facility-level models including facility type and the continuous county social-vulnerability Q index, no coefficient for social vulnerability remained statistically significant after FDR adjustment; the smallest FDR-adjusted p value was 0.071. The adjusted hospital coefficient for infrastructure and resources remained positive at 18.3 percentage points (95% CI 6.4 to 30.1; FDR-adjusted $p=0.031$).

Associations involving social vulnerability were sensitive to exclusion of Ahvaz and were therefore not interpreted as stable county-level gradients. Overall, the contextual analyses provided no evidence of a consistent association between the county-level social-vulnerability index and facility adaptive-capacity scores.

Discussion

Principal findings

This study assessed the adaptive capacity of 52 healthcare facilities in dust-storm-prone Khuzestan to manage air-pollution-related health pressures. The clearest facility-type difference was observed for infrastructure and resources, with hospitals scoring approximately 20 percentage points higher than county health-centre units. This was the only domain-level comparison that remained statistically significant after FDR adjustment in the primary analysis and was associated with a large standardized effect. The direction and approximate magnitude of the difference were maintained across the prespecified sensitivity analyses, although FDR-adjusted statistical significance was not retained in

every analysis. Response and recovery capacity also favoured hospitals, but the estimate was less precise and did not remain statistically significant after adjustment for multiple comparisons. Across all facilities, the lowest mean scores were observed for air-quality monitoring and evaluation, infrastructure and resources, and response and recovery capacity. Item-level findings further identified specific operational gaps: only 38.5% of facilities reported regularly receiving air-quality data from reliable sources, 30.8% reported using air-quality information to prioritize services, and 36.5% reported adequate equipment to receive patients affected by air pollution.

The secondary managerial findings broadly paralleled the facility-capacity results but should not be regarded as independent confirmation. Hospital managers reported substantially higher perceived preparedness than health-centre managers. Among the archived domain-level correlations, perceived preparedness showed the strongest positive associations with infrastructure and resources, response and recovery capacity, and air-quality monitoring and evaluation. These correlations indicate descriptive correspondence between managers' overall perceptions and several assessed operational domains, but their interpretation is limited by the shared respondent and organisational context and by the absence of recoverable item-level data for the perceived-preparedness instrument. They were therefore not interpreted as measures of domain importance, evidence of construct validity, or indications of causal relationships.

Infrastructure, resources, and operational response

The disparity in infrastructure is evident within the functional organization of the provincial health system. Hospitals are more likely than county health centres to possess emergency departments, oxygen and respiratory-support systems, high-capacity ventilation and utility networks, diagnostic services, inpatient surge arrangements, and formal incident-management structures. International guidelines similarly emphasize the importance of safe indoor environments, resilient energy and water systems, ventilation and filtration, continuity of essential supplies, workforce protection, and surge capacity as fundamental components of climate-resilient healthcare facilities [10,11,16,17,21]. The consistency of the infrastructure estimate, following the aggregation of East and West Ahvaz, the use of corrected aggregate domain totals, and comparisons within matched operational areas, mitigates concerns that the finding is solely due to the concentration of hospitals in the provincial capital.

However, this finding should be interpreted as a difference in assessed capacity rather than as evidence that hospitals would perform better during an actual dust emergency. The mere availability of equipment or plans does not guarantee functionality under stress, adequacy relative to patient demand, maintenance quality, staff competence, or continuity during simultaneous disruptions in electricity, water, supply chains, and workforce. Conversely, the lower scores of health centres should not be

657 construed as a failure to replicate hospital functions. County-level health-network units have distinct
658 mandates but remain crucial for risk communication, continuity of chronic-disease care, triage,
659 referral, community outreach, medication access, and protection of vulnerable populations.

660 Capacity standards should therefore be specific to the role. Hospitals require surge capacity,
661 respiratory support, inpatient continuity, and resilient referral arrangements. Health centres need
662 reliable alerts, protected consultation spaces, continuity of essential outpatient services, community
663 communication, appropriate triage capacity, and clear escalation and referral pathways. The results
664 highlight an infrastructure gap between sectors but do not suggest that a uniform infrastructure package
665 is suitable for every facility.

666 Response and recovery capacity showed a moderate estimated difference favouring hospitals, but the
667 estimate was imprecise and did not remain statistically significant after multiplicity adjustment. This
668 uncertainty advises against considering the finding as definitive, yet its direction and magnitude
669 warrant operational attention. Generic emergency plans should be adapted into dust- and pollution-
670 specific triggers, including alert thresholds, escalation levels, protected indoor zones, occupational
671 exposure controls, surge and referral pathways, continuity of oxygen and essential medicines,
672 alternative staffing arrangements, and structured post-event review. These functions align with WHO
673 climate-resilient facility guidance, the BRACE framework, and the dust-health mitigation literature,
674 which conceptualize preparedness as a linked cycle of anticipation, response, learning, and adaptation
675 [10–12,15].

676 **Air-quality intelligence, communication, and evaluation**

677 Air-quality monitoring and evaluation exhibited the lowest overall mean, with item analysis revealing
678 that the primary deficiency extended beyond the mere absence of facility-owned sensors. The more
679 significant shortcoming was the inability to translate reliable external environmental data into
680 operational decisions. An effective alert system necessitates a designated recipient, a validated
681 information source, predefined thresholds, actions aligned with the facility's role, redundant
682 communication channels, documentation of implementation, and evaluation of whether the response
683 adequately protected patients and staff. The WHO and BRACE similarly conceptualize surveillance,
684 early warning, communication, implementation, and evaluation as components of an integrated
685 decision cycle rather than isolated administrative tasks [10–12].

686 This distinction holds significance for policy formulation. The installation of additional monitoring
687 instruments will yield limited benefits if the data are not timely, trusted, interpreted, and linked to
688 authoritative action. Province-wide protocols should delineate who receives alerts, how uncertainty is
689 communicated, and when to modify outpatient activities, ventilation practices, filtration, staff

690 protection, referral readiness, and public messaging. Additionally, they should specify who records
691 compliance. Following each major episode, facilities should review alert receipt, activation time,
692 service disruptions, patient flow, resource mobilization, and deviations from protocol. Such an
693 approach would transition monitoring from passive awareness to organizational learning.
694 High scores in training, communication, and intersectoral collaboration warrant cautious interpretation.
695 Several checklist items exhibited ceiling effects, and the collaboration domain, comprising only three
696 items, demonstrated low internal consistency in the main sample. The mere existence of a reported
697 committee, training program, or cooperation agreement does not guarantee frequency, quality,
698 authority, interoperability, or performance under pressure. For operational checklists, internal-
699 consistency coefficients should not be regarded as evidence of unidimensional latent constructs;
700 content coverage, response-process evidence, dimensional assessment, and validation against
701 observable performance remain essential [24–30]. Future assessments should therefore verify meeting
702 frequency, staff participation, alert-transmission time, exercise performance, joint decision logs,
703 corrective actions, and after-action reviews, rather than relying solely on the reported existence of
704 arrangements.

705 **Managerial perception and prioritization**

706 Managers' perceived preparedness was substantially higher among hospitals than among county
707 health-centre units, broadly paralleling the stronger assessed infrastructure observed in hospitals.
708 Among the archived domain-level correlations, perceived preparedness was most strongly associated
709 with infrastructure and resources, response and recovery capacity, and air-quality monitoring and
710 evaluation. These associations are reported as secondary descriptive findings and should not be
711 interpreted as measures of domain importance, evidence of construct validity, or indications of causal
712 relationships.

713 Interpretation of these correlations is limited by the shared respondent and organisational context of the
714 two assessments. Both instruments drew information from facility management, creating the
715 possibility of common-method variance, consistency effects, recall bias, and social-desirability bias
716 [32]. In addition, item-level responses to the perceived-preparedness instrument were not available in
717 the revision-stage analytical archive, preventing independent examination of response patterns,
718 influential observations, manager-level confounding, or additional measurement properties. The
719 archived correlations therefore provide contextual evidence of correspondence between assessed
720 capacity and managerial perception rather than independent validation of the adaptive-capacity
721 domains.

722 More complex latent-variable modelling was not pursued because the sample size and recoverable
723 measurement data were insufficient to support a reproducible multidomain latent model.

724 **Equity and environmental context**

725 The lack of a stable correlation between county social vulnerability and facility capacity should not be
726 construed as evidence that vulnerability is insignificant. The contextual sample size was limited,
727 multiple facilities shared identical county values, proxy values were necessary for two newer counties,
728 and Ahvaz exhibited high published vulnerability alongside a concentration of referral hospitals and
729 institutional resources. These factors diminish statistical independence and suggest that urban referral
730 capacity may obscure community-level disadvantages. The Khuzestan social-vulnerability index
731 remains pertinent because identical facility scores can yield different outcomes in populations with
732 varying socioeconomic resources, housing conditions, health needs, and capacities to avoid exposure
733 or travel for care [33].

734 Equity-oriented planning should integrate capacity scores with catchment population, service
735 criticality, referral role, remoteness, chronic-disease burden, and social vulnerability, rather than
736 distributing resources uniformly. More detailed deprivation measures and patient-origin data would aid
737 in distinguishing the vulnerability of the county where a facility is located from that of the population
738 it actually serves. Multilevel or spatial modeling may become suitable when a larger number of
739 facilities, repeated observations, and catchment-level data are available.

740 The study was conducted in a dust-prone province, yet no facility-specific dust coefficient was
741 estimated. This restraint enhances rather than diminishes the analysis. Assigning historical Ahvaz
742 particulate-matter values to remote facilities would introduce ecological and temporal
743 misclassification, potentially creating false exposure–capacity associations. The subsequent analytical
744 step should involve prospective linkage of hourly PM₁₀, PM_{2.5}, visibility, meteorological conditions,
745 and classified dust events with emergency visits, occupancy, oxygen use, medication demand, staff
746 absence, transfer delays, canceled services, indoor air quality, protocol activation, and facility action
747 logs. Such event-linked data are essential to ascertain whether assessed preparedness translates into
748 continuity, safety, and recovery during actual pollution episodes.

749 **County-level social vulnerability**

750 County-level analyses did not show a consistent monotonic association between social vulnerability
751 and the seven adaptive-capacity domains. Among the 22 current-county summaries for health-network
752 units, Spearman correlation coefficients ranged from −0.259 to 0.202; among the 21 hospital county
753 summaries, coefficients ranged from −0.105 to 0.331. None of the correlations remained statistically

754 significant after FDR adjustment, and the bootstrap confidence intervals were generally wide and
755 included zero.

756 In exploratory facility-level models including facility type and the continuous county social-
757 vulnerability Q index, no social-vulnerability coefficient remained statistically significant after FDR
758 adjustment; the smallest FDR-adjusted p value was 0.071. The adjusted hospital coefficient for
759 infrastructure and resources remained positive at 18.3 percentage points (95% CI 6.4 to 30.1; FDR-
760 adjusted p=0.031).

761 The estimated associations with social vulnerability were sensitive to geographic specification.
762 Excluding facilities assigned proxy Q values for Karkheh and Dezpart strengthened several positive
763 associations, whereas excluding Ahvaz attenuated or reversed them. This marked sensitivity to the
764 geographic specification precluded interpretation of the observed associations as stable county-level
765 gradients. Overall, the contextual analyses did not provide evidence of a consistent association
766 between county-level social vulnerability and facility adaptive-capacity scores.

767 **Comparison with previous evidence**

768 The present findings are consistent with earlier qualitative evidence from Iran. Allahbakhshi et al. [13],
769 in a 2016–2017 qualitative study involving national and provincial stakeholders and participants from
770 Khuzestan, identified preparedness challenges related to risk assessment, knowledge management,
771 organizational arrangements, coordination and communication, resources, and monitoring and
772 evaluation. The present facility-level assessment extends this evidence by quantitatively demonstrating
773 that reported adaptive-capacity gaps were not uniformly distributed across functions. Air-quality
774 monitoring and evaluation, infrastructure and resources, and response and recovery capacity had the
775 lowest mean domain scores, whereas staff training and empowerment and public awareness and risk
776 communication were comparatively higher. This pattern suggests that reported training and
777 communication capacities may be more developed than the operational systems needed to translate
778 environmental information into facility actions.

779 These findings are also consistent with the systematic review by Sarani et al. [15], which identified risk
780 and vulnerability assessment, early-warning systems, intersectoral coordination, strengthening of
781 primary healthcare facilities, staff training, ventilation, resource allocation, forecasting, and monitoring
782 among important measures for mitigating dust-related risks in healthcare settings. The present results
783 identify gaps in several of these operational functions in Khuzestan. In particular, only 30.8% of
784 facilities reported using air-quality data to set priorities for service provision, and 46.2% reported using
785 such information to evaluate the effectiveness of their response. These findings suggest a gap between

786 reported preparedness structures and the routine operational use of environmental intelligence for
787 decision-making and evaluation.

788 The substantially higher infrastructure and resources score observed in hospitals than in county health
789 centres further indicates that adaptive capacity may differ by facility function and level of care. This
790 difference was large in the primary analysis and remained similar in direction and magnitude across
791 the prespecified sensitivity analyses. Rather than establishing a general hierarchy of preparedness
792 across healthcare sectors, these findings identify infrastructure and resource capacity in county health
793 centres as a specific priority for further assessment and strengthening. This is particularly relevant
794 given previous literature emphasizing the importance of resilient primary healthcare facilities in
795 maintaining service continuity during dust and other environmental hazards [15].

796 **Strengths and limitations**

797 Strengths of this study include comprehensive inclusion of the verified 52-unit study frame,
798 representation of both hospitals and county-level health-network units, reconstruction of domain scores
799 from item-level responses, transparent documentation of data corrections and discrepancies, and
800 reporting of effect estimates with confidence intervals. The analytical approach also incorporated
801 multiplicity adjustment, bootstrap and permutation analyses, geographically paired comparisons, and
802 prespecified sensitivity analyses, while explicitly distinguishing assessed adaptive capacity from
803 observed performance during actual dust events. The direction and approximate magnitude of the
804 infrastructure difference were maintained across the prespecified sensitivity analyses, although
805 multiplicity-adjusted statistical significance was not retained in every analysis.

806 Several limitations should be considered. The cross-sectional design precludes causal inference and
807 does not capture temporal changes or demonstrated resilience during actual dust events. Each study
808 unit was represented primarily by one senior manager or designated official, and supporting
809 documentary or observational evidence was not uniformly available across facilities and items,
810 introducing the possibility of reporting, recall, and social-desirability bias. In addition, the analytical
811 dataset combined “no” and “do not know” responses as non-affirmative, preventing distinction
812 between an explicitly reported absence of capacity and respondent uncertainty about whether that
813 capacity was present. Six stored facility-domain totals differed from totals reconstructed from item-
814 level responses; therefore, item-derived scores were used for the primary analyses and corrected
815 aggregate totals were examined in sensitivity analyses. Four groups of study units had identical 40-
816 item response profiles. Although these represented separately identified and independently assessed
817 units and were therefore retained, the available data could not determine whether the identical profiles
818 reflected genuinely standardized practices or duplication in reporting.

819 The researcher-developed instruments also require further measurement evaluation. Archived expert-
820 review and pilot records supported the reported content-validity and internal-consistency assessments,
821 but the exact procedures used to aggregate the reported overall CVR and CVI values could not be
822 reconstructed from the available documentation. The seven adaptive-capacity domains were content-
823 defined operational groupings and were not empirically confirmed as unidimensional latent constructs.
824 This limitation is particularly relevant to the three-item intersectoral-collaboration domain, for which
825 internal-consistency estimates should be interpreted cautiously. Future studies should undertake more
826 comprehensive evaluation of content mapping, cognitive response processes, dimensionality, reliability
827 appropriate to the intended constructs, measurement invariance, and criterion validity against
828 independently measured operational outcomes [25–31].

829 Finally, the contextual analyses were constrained by the small number of independent county contexts,
830 assignment of the same county-level vulnerability value to multiple facilities, use of parent-county
831 proxy values for newer counties, and the influence of Ahvaz on some estimates. Social-vulnerability
832 associations were consequently sensitive to geographic specification and should not be interpreted as
833 stable county-level gradients. Temporally and spatially matched environmental exposure data and
834 objective measures of service disruption during dust events were also unavailable, preventing
835 assessment of facility-specific exposure–capacity relationships or demonstrated operational resilience.

836 **Implications for policy and practice**

837 The findings identify several priorities for strengthening facility adaptive capacity to air-pollution and
838 dust-related health emergencies in Khuzestan. First, a province-wide dust-health alert protocol could
839 link validated environmental information and officially defined alert levels to predefined operational
840 actions within healthcare facilities. Such a protocol should specify responsibilities, communication
841 pathways, escalation procedures, and actions appropriate to different facility types rather than relying
842 on informal or discretionary responses to deteriorating air quality.

843 Second, the comparatively low infrastructure and resources scores, together with the substantially
844 lower scores observed in county health centres than in hospitals, indicate a particular need to assess
845 and strengthen operational capacity in county-level health-network units. Priorities may include
846 ventilation and protected indoor spaces, continuity of electricity and essential supplies, equipment and
847 procedures appropriate for managing patients affected by air pollution, primary-care triage capacity,
848 and reliable referral arrangements for patients requiring higher levels of care. The specific package
849 required at each facility should reflect its service role, patient population, and position within the
850 referral system.

851 Third, the low scores for air-quality monitoring and evaluation indicate that environmental intelligence
852 should be more systematically incorporated into facility operations. Air-quality information could be
853 linked to service planning, occupational protection measures, patient and public risk communication,
854 activation of preparedness procedures, and post-event evaluation. In particular, the low proportion of
855 facilities reporting use of air-quality information to prioritize services suggests that improving access
856 to environmental information alone may be insufficient unless alerts are explicitly linked to predefined
857 operational decisions.

858 Fourth, resource allocation should consider facility capacity alongside broader health-system and
859 equity considerations. Although this study did not demonstrate a stable statistical association between
860 the county-level social-vulnerability index and adaptive capacity, vulnerability remains relevant to
861 preparedness planning. Decisions about strengthening facilities may therefore reasonably consider
862 factors such as population vulnerability, catchment size, service criticality, remoteness, referral
863 function, and local hazard burden together with demonstrated capacity deficits. These factors should be
864 regarded as complementary planning criteria rather than as relationships established by the present
865 analysis.

866 Programme monitoring should emphasize measurable and auditable indicators rather than broad
867 classifications of facilities as “prepared” or “unprepared.” Potential indicators include the proportion of
868 facilities receiving validated environmental alerts within a predefined time interval; the proportion
869 activating a documented response procedure; time from alert receipt to operational action; availability
870 and continuity of essential medicines, oxygen where clinically relevant, electricity, and communication
871 systems; completion of scenario-based staff exercises; time required to mobilize additional resources;
872 referral or transfer delays; and completion of documented after-action reviews. Where technically
873 feasible, environmental performance indicators, such as particulate concentrations within designated
874 protected indoor areas, could also be incorporated into future prospective monitoring. Repeated
875 assessment of these indicators would permit evaluation of changes in operational performance over
876 time and provide evidence on whether assessed adaptive capacity translates into demonstrated
877 resilience. The present cross-sectional study provides a baseline against which such longitudinal
878 improvements could be evaluated.

879 Implementation should also distinguish responsibilities at the provincial health-system level from those
880 of individual facilities. Provincial authorities are positioned to maintain validated environmental-
881 information channels, establish operational alert levels, define minimum preparedness standards,
882 coordinate referral pathways and supply systems, and monitor system-wide performance. Individual
883 facilities should translate these standards into procedures appropriate to their service role, document

884 activation and implementation, protect patients and staff, maintain essential services, and report
885 operational disruptions and lessons identified after events. A clearly defined division of responsibilities
886 may reduce dependence on informal managerial initiative and support a more standardized and
887 accountable dust-health preparedness system across the province.

888 **Future research**

889 Future research should incorporate repeated assessments of facilities before, during, and after
890 significant pollution events. Instruments must maintain distinct codes for "no" and "do not know,"
891 document the evidence—either documentary or observational—supporting each response, and preserve
892 item-level data from all questionnaires. Objective measures of facilities should encompass ventilation
893 performance, indoor particulate concentrations, the availability and functionality of respiratory-support
894 equipment, the continuity of essential utilities, staff attendance, stock interruptions, response-plan
895 activation, and after-action findings.

896 A more extensive longitudinal dataset would enable the evaluation of responsiveness to change,
897 predictors of improvement, clustering within counties, and the interaction between facility roles and
898 community vulnerability. Event-linked environmental and service data would facilitate testing adaptive
899 capacity against outcomes such as patient volume, waiting time, transfer delay, service cancellation,
900 occupational absence, and continuity of chronic-disease care. These advancements are essential for
901 transitioning from an assessment of preparedness structures to an evaluation of demonstrated health-
902 service resilience.

903 **Conclusions**

904 In an evaluation of 52 facilities in the dust-storm-prone region of Khuzestan, hospitals demonstrated
905 significantly stronger infrastructure and resources compared to county health centres. Hospital
906 managers also reported a higher level of perceived preparedness. System-wide, the most defensible
907 priorities identified were infrastructure, the routine operational use of air-quality intelligence, and
908 response and recovery capacity. The findings advocate for a coordinated programme that integrates
909 validated dust and air-quality alerts with facility-specific actions, enhances role-appropriate capacity in
910 primary care, and allocates investment based on hazard, vulnerability, service criticality, and referral
911 responsibility. As the study assessed preparedness rather than actual event performance, it is necessary
912 to conduct prospective repeated assessments with recoverable item-level data, linked to environmental,
913 patient-flow, and service-continuity outcomes, to ascertain whether these capacities contribute to
914 resilient healthcare delivery.

915

916 **List of abbreviations**

917 BRACE: Building Resilience Against Climate Effects; CDC: Centers for Disease Control and
918 Prevention; CI: confidence interval; CVI: content validity index; CVR: content validity ratio; FDR:
919 false discovery rate; PM: particulate matter; Q: social-vulnerability index; SD: standard deviation;
920 STROBE: Strengthening the Reporting of Observational Studies in Epidemiology; WHO: World
921 Health Organization.

922 **Declarations**

923 **Ethics approval and consent to participate**

924 The study was approved by the Ethics Committee of Ahvaz Jundishapur University of Medical
925 Sciences (IR.AJUMS.REC.1402.190). Written informed consent was obtained from all participants.

926 **Consent for publication**

927 Not applicable.

928 **Availability of data and materials**

929 The dataset is not publicly available because facility-level records may permit institutional
930 identification; de-identified analytical data and code may be available from the corresponding author
931 on reasonable request and subject to institutional approval

932 **Competing interests**

933 The authors declare that they have no competing interests.

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940 **Authors' contributions**

941 MM contributed to conceptualisation, methodology, drafting, and critical revision. BK and FR
942 contributed to methodology, formal analysis, validation, and critical revision. BS contributed to
943 investigation, resources, and critical revision. FA, MHS, and SS contributed to clinical validation and
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945 investigation, data curation, and critical revision. NK contributed to investigation, data curation, formal
946 analysis, visualisation, drafting, and critical revision. MAK contributed to conceptualisation, funding

947 acquisition, project administration, supervision, methodology, and critical revision. All authors read
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953 **Additional files**

954 Additional file 1: English translations and original Persian versions of the study instruments.
955 Additional file 2: Supplementary statistical results, item-level comparisons, sensitivity analyses,
956 county-level contextual analyses, and measurement-property summaries.

957

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Figure legends

Figure 1. Geographic distribution of assessed healthcare facilities in Khuzestan Province.

Panel A illustrates the geographical position of Khuzestan Province within Iran. Panel B depicts the distribution of 24 county-level health-network units and 28 hospitals across the 22 county contexts currently included in the study. Distinct symbols are used to differentiate facility types, and an inset provides an enlarged view of Ahvaz, where multiple study facilities were situated. East and West Ahvaz were evaluated separately, yet they were associated with the same county context. Mahshahr

1074 and Bandar Imam were considered distinct operational areas within Bandar Mahshahr County. The
1075 map serves a descriptive purpose and was not employed to estimate geographic accessibility or
1076 environmental exposure.

1077 **Figure 2. Hospital-minus-health-centre differences in normalized adaptive-capacity domain**
1078 **scores.**

1079 Points show mean differences in percentage points and horizontal bars show 95% confidence intervals.
1080 Positive values indicate higher mean scores among hospitals.

1081

1082

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