Full title: A multisectoral data integration framework and geospatial visualisation for last-mile heat-health decision making: A pilot deployment study in Rajasthan, India

Short title: Geospatial visualization for heat-health decision making in Rajasthan

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Abstract

Adaptation for extreme heat depends on identifying and responding to populations most vulnerable to heat-related illnesses. Yet, in many low- and middle-income countries the data needed to assess vulnerability remains fragmented across disconnected information systems. As a result, frontline health officials plan their response strategies using limited, underreported, and retrospective surveillance data rather than prospective assessments of vulnerability. For India, a country at the center of multiple climate-sensitive illnesses, this study aimed to develop an interoperable data integration framework for the first time at the sub-district level; co-design a human-centered geospatial dashboard for heat-health planning; and evaluate its utility during statewide deployment through changes in officials' understanding of vulnerability and planning orientation.

The Heat-Health Vulnerability Index (HHVI) was designed by Khushi Baby through a five-stage human-centered process, in partnership with the State Government of Rajasthan's Department of Medical, Health, and Family Welfare. HHVI measures vulnerability through 21 indicators across data systems, with independent spatial identifiers and reporting cadences including ERA5 climate reanalysis, remote sensing, maternal and child health registries, non-communicable disease data, and demographic health survey data. All systems were resolved to an administrative block boundary, producing a choropleth dashboard and linking vulnerability grades to existing Heat Action Plan protocols. HHVI revealed non-obvious spatially heterogeneous patterns of vulnerability within districts. High-vulnerability blocks consistently appeared within largely moderate-risk districts, driven by multi-causal combinations that no single data source captured.

Structured review sessions with district officials prior to deployment surfaced a gap in the HHVI dashboard between visualizing insights, and using the insights to plan, execute, and track responses. This informed the development of an action feature (Spark Action) to schedule existing heat actions from the dashboard insights page itself.

The dashboard was deployed through structured full-day workshops across all administrative divisions of Rajasthan. The workshops brought together 129 government health officials across 44 districts, who are collectively responsible for health service delivery to over 80 million people. Officials navigated the dashboard using their district data and produced district-level heat season plans. Pre- and post-workshop assessments were administered to measure changes in vulnerability conceptualization and planning orientation.

Across 101 officials with matched pre- and post-assessments: correct conceptualization of vulnerability rose by 20.8 percentage points ($p<0.001$), and vulnerability-based planning prioritization increased by 17.8 percentage points ($p<0.001$), with case-count based planning declining from 23.8% to 14.9% , and correct identification of the first step in heat-season planning increased from 85.1% to 94.1% (+8.9 percentage points, $p=0.027$).

In summary, we demonstrated the feasibility of an integrated and actionable heat-health dashboard for Rajasthan's sub-districts along with measurable shifts in health official knowledge and practices. Three design principles emerged for integrating and applying climate-health data for frontline government planners: geographic granularity must match the user's accountability level; confidence in integrated outputs is established through local knowledge validation; and for operational users, visualization alone does not guarantee response in the absence of clear decision aids.

Keywords: Vulnerability Visualization, Climate x Health, Decision-support tool, Rajasthan India, Extreme heat preparedness, Sub-district level vulnerability mapping, Data to Action, Risk-based prioritization tool

1. Introduction

Climate change is increasingly affecting health globally, with extreme heat emerging as one of the leading climate-driven causes of excess mortality. Between 2000 and 2019, approximately 489,000 heat-related deaths occurred annually, 45% of them in Asia (1). The urgency is underscored by the fact that the past decade (2015–2024) was the hottest on record globally. India is among the most heat-exposed nations with approximately 57% of the districts, home to 76% of the population, classified as high to very high heat risk (2). Beyond its health impacts, heat stress is projected to cost India the equivalent of 35 million full-time jobs and a 4.5% reduction in GDP by 2030 (3). Within this national context, Rajasthan, India's largest state and home to 81 million people, presents unique challenges (4). More than 88% of Rajasthan's districts already experience drought-like conditions and an estimated 64.9% of residents are outdoor workers in mining, agriculture, and construction who face severe occupational heat exposure (2,4) .Average temperatures are projected to increase by 1.8–2.1°C by 2035, further intensifying heat-related risks in an already highly vulnerable region (2).

Frontline government health officials, including district medical officers, block chief medical officers (BCMOs), and program coordinators, are responsible for translating national climate-health programming into community response. Their responsibilities include planning seasonal preparedness activities, allocating resources (such as oral rehydration solution (ORS), cooling supplies, and personnel), and implementing interventions such as local awareness campaigns before and during heat seasons. However, these operational decisions are currently made in a limited data environment. Heat preparedness planning in India, as across much of the low- and middle-income countries, continues to rely on retrospective aggregate data from the previous season, subnational-level advisories, and standardized surveillance reports (5). These approaches treat risk as uniform within an administrative unit and respond to what happened rather than anticipating where and for whom the highest risk will emerge (6).

As a result, resources are allocated based on reported cases rather than prospective vulnerability. A 2022 knowledge, attitudes, and practices survey of Indian health professionals found that while 80.9% linked heat illness to climate change, fewer than half were aware of local heat action plans reflecting a systemic gap between available climate information and its operational uptake (7). While heat-health vulnerability assessments and climate-risk mapping efforts have expanded globally, there remains limited evidence on how such information can be translated into operational planning tools that are routinely used by frontline government decision-makers in resource-constrained settings.

Addressing this gap requires tools that integrate complex climate, health and socioeconomic data into formats that are understandable, actionable, and relevant to local planning processes. This paper describes the design and deployment of the Heat-Health Vulnerability Index (HHVI) dashboard, a sub-district level geospatial visualization tool developed by Khushi Baby, a not-for-profit organization, working in formal partnership with the Government of Rajasthan's Department of Medical, Health, and Family Welfare. The dashboard integrates climate exposure, health sensitivity, and adaptive capacity indicators from seven independent government data systems, into a composite vulnerability map at block levels (below districts). It was developed through a human-centered design process spanning field scoping, co-design, prototyping, and participatory statewide deployment and evaluated through structured pre- and post-workshop assessments with 129 government health officials across all divisions of Rajasthan.

The objectives of this study were to design a locally contextualized heat-health vulnerability dashboard and evaluate its utility as a planning and decision-support tool for frontline government health officials. We assessed whether the dashboard improved participants' understanding of spatial patterns of heat vulnerability and their ability to identify priority areas for intervention. This study evaluated how an integrated vulnerability framework can be translated into an operational planning tool and incorporated into routine government decision-making through statewide deployment. The study also investigated design principles for operationalizing climate-health vulnerability information within government health systems.

2. Methods

2.1 Study Setting

This study was conducted in Rajasthan, India, a state characterized by substantial climatic, geographic, and socioeconomic heterogeneity that contributes to differential vulnerability to extreme heat (8). The work was undertaken in partnership with the Department of Medical, Health and Family Welfare (DoMHFW), Government of Rajasthan, to support sub-district level heat-health preparedness and response planning. This study was implemented as part of the vulnerability assessment and capacity building initiative implemented under India's National Programme on Climate Change and Human Health (NPCCHH).

2.2 Study Design

This study employed a participatory human-centered design (HCD) approach to develop and evaluate the Heat-Health Vulnerability Index (HHVI) dashboard and associated decision-support tools for government health officials to manage heat-related illnesses. Participatory HCD emphasizes the active involvement of end users throughout problem definition, solution development, testing, and refinement to ensure that resulting interventions are contextually relevant, usable, and responsive to operational needs. The design process was structured around the five phases of design thinking including Empathize, Define, Ideate, Prototype, and Test (9).

The objective was to co-design a solution that emerged from the HCD process to address heat-health vulnerability. Specific opportunity areas included reforming the process for assessment and visualization of relevant multi-sectoral data for the program to ensure it remains scientifically robust while being interpretable, actionable, and operationally relevant for district and block-level health authorities responsible for heat preparedness and response.

Participants were government health officials assessed in their professional capacity; no personal health data were collected. Pre- and post-workshop assessments were administered to measure professional knowledge and stated planning orientation as part of routine program monitoring and improvement. Participation was voluntary; officials were informed that responses would be used for program improvement and that no individually identifiable data would be published.

This work was conducted as part of routine government heat-health planning, capacity building, and program implementation activities undertaken in partnership with the Government of Rajasthan. Consistent with the Indian Council of Medical Research (ICMR) National Ethical Guidelines for Biomedical and Health Research Involving Human Participants (2017), the activities described here constituted program evaluation and quality improvement activities involving government employees acting in their professional roles rather than human subjects research and therefore, formal institutional ethics committee approval was deferred. Documentation supporting implementation under routine government programming is provided in Additional Material 1.

2.3 Empathize: Understand the Data Landscape and User Needs

Between January 2025 and January 2026, 10 structured scoping visits were conducted in districts representing the geographic, climate and socioeconomic diversity of Rajasthan, including Alwar, Churu, Jaipur, Jhunjhunu, Jodhpur, Phalodi, and Udaipur. In India's public health system, districts are subdivided into administrative blocks, which are responsible for frontline planning and resource allocation.

Key informants included District Collectors, Chief Medical and Health Officers (CMHOs), Deputy Chief Medical and Health Officers serving as district heat-health nodal officers, Block Chief Medical Officers (BCMOs), district data managers, district hospital administrators, Accredited Social Health Activists (ASHAs), and Auxiliary Nurse Midwives

(ANMs). These stakeholders were selected because of their direct involvement in heat-health surveillance, preparedness planning, reporting, and service delivery.

Semi-structured interviews were conducted with key informants focused on existing heat-health workflows, reporting mechanisms, decision-making processes, data availability, operational constraints, and opportunities for integrating vulnerability information into routine planning activities. Additional participants were identified through snowball sampling to capture perspectives not represented in the initial stakeholder list. Within each district at least two health facilities were visited, including one district-level facility and one block-level facility (S1 Fig.).

The objective was to understand the operational reality of heat preparedness planning before any visualization was designed, an approach consistent with co-design frameworks in public health visualization (10) .The scoping visits confirmed that frontline officials responsible for heat preparedness make planning and resource allocation decisions at the administrative block level, yet the information needed to make these decisions are dispersed across multiple fragmented systems. Officials relied on separate data sources, including Integrated Health Information Platform for disease surveillance, NCD registers for chronic disease burden, Community Health Integrated Platform (CHIP) for community health worker activity. However, these systems operated independently and lacked a common mechanism for assessing heat-health vulnerability at the administrative block level. Consequently, officials relied on reported heatstroke case counts for planning, despite widespread recognition that heat-related illnesses are substantially underreported within routine health facility data. These findings established the need for a block-level vulnerability framework capable of integrating multiple data sources into a single operational planning tool.

2.4 Define: Problem Statement and Design Requirements

Findings from the scoping phase produced a clear problem definition: officials responsible for heat preparedness had access to multiple government information systems but lacked an integrated view of vulnerability at the administrative block level, where planning authority and resource allocation decisions are exercised. Existing planning processes relied primarily on retrospective heatstroke case counts, district-level advisories, and program-specific datasets, none of which provided a comprehensive understanding of where future heat-health risks were most likely to emerge.

To address this gap, we sought to develop both an interoperable data integration framework capable of combining climate, health, and socioeconomic information at the block level and a visualization system that would make the resulting outputs understandable and actionable for frontline decision-makers.

Four design requirements were formalized from stakeholder consultations and field observations.

Table 1.Design requirements for a decision-making tool

DR1: Data granularity: Heat-health information needed to be available at the administrative block level, reflecting the	DR2: Interpretability: Information needed to be presented in a format that could be readily understood without specialized

operational jurisdiction of frontline planners.	analytical training.
DR3: Local validity: Outputs needed to align with officials' contextual knowledge of their districts to support confidence in the resulting vulnerability classifications.	DR4: Operational actionability: The tool needed to connect vulnerability information to specific preparedness and response activities rather than simply describing risk.

These requirements informed subsequent decisions regarding data integration, index construction, dashboard design, and statewide deployment.

2.5 Ideate: Designing the Integration Framework, Index, and Dashboard

The primary technical challenge was that the datasets required to characterize heat-health vulnerability were distributed across multiple government systems that differed in reporting cadence, spatial resolution, and administrative identifiers (S1 Table). Climate datasets were organized as gridded geographic surfaces, health program data were reported through facilities, and demographic information was collected through household and community-level systems.

To enable integration, all datasets were resolved to a common geographic unit: the administrative block. Standardized Government of Rajasthan block boundary shapefiles were used as the reference geography, allowing indicators from multiple sources to be spatially harmonized and aggregated.

Indicator selection and index construction

The HHVI was constructed using the Intergovernmental Panel on Climate Change (IPCC) AR4 vulnerability framework, in which vulnerability is conceptualized as a function of exposure, sensitivity, and adaptive capacity (11,12) .

Vulnerability = Function [Exposure (+), Sensitivity (+), Adaptive Capacity (-)]

Exposure refers to the degree to which an area is affected by climatic events; sensitivity refers to the presence of populations more likely to experience adverse health outcomes from extreme heat; and adaptive capacity refers to the ability of individuals and communities to cope with potential heat impacts.

The additive vulnerability framework (IPCC AR4) was selected over the multiplicative AR5 risk formulation specifically because it keeps each domain's contribution - exposure, sensitivity, adaptive capacity independently visible in the dashboard. This design choice emerged directly from stakeholder feedback indicating that officials needed to understand not only which blocks were vulnerable, but also why vulnerability was occurring.

The vulnerability index was developed through an iterative process integrating literature review, expert advisory input, and government feedback. Over 40 indicators (S2 Table) spanning climate exposure, population health, and socioeconomic conditions were assembled, drawing on established composite index frameworks (11). Indicators were progressively narrowed based on three criteria: data completeness and quality, correlation and VIF analyses to reduce redundancy, and causal pathway relevance to heat-health outcomes . The resulting 21 indicators (Table 2) were reviewed by a Scientific Advisory Committee (S3 Table) for epidemiological relevance and alignment with decision-making needs of block- and district-level planners.

Table 2. The final HHVI included 21 indicators organized across three domains: exposure, sensitivity, and adaptive capacity

Exposure	**Sensitivity**	**Adaptive Capacity**
Wet Bulb Globe Temperature	Children under 5	Household potable water access
Warm nights - duration and frequency	Pregnant Women	Unstable household electricity
Built-up index (NDBI)	Elderly >60	Housing thermal exposure
Vegetation index (NDVI)	Hypertension prevalence	Access to social schemes related to heat
Diurnal temperature range	Diabetes prevalence	Literacy levels
Heatwave - duration and frequency	Marginalized population	Primary transportation
	Hazardous occupations	Driving time to nearest tertiary hospital
	Population density	

All variables were transformed using Robust Scaling to minimize the distorting effects of outliers by centering the data around the median and scaling it according to the interquartile range. Principal Component Analysis (PCA) was applied independently within the exposure, sensitivity, and adaptive capacity domains to reduce dimensionality and compute domain-specific composite scores. Components were retained based on the Kaiser criterion and required to have their first principal component explain at least 60% of within-domain variance, ensuring dimensional reduction did not compromise interpretability. The respective loadings can be found in S2 Fig. The resulting domain-specific scores were then combined according to the IPCC AR4 vulnerability framework, whereby vulnerability increases with greater exposure and sensitivity and decreases with greater adaptive capacity.

The resulting Heat Health Vulnerability Index (HHVI) scores were standardized and classified into four relative vulnerability categories (Low, Moderate, High, and Very High) using quartile distributions across all blocks in Rajasthan. Relative classification was selected because stakeholders consistently framed planning decisions in comparative terms, asking which blocks should be prioritized relative to others within their district or across the state.

Dashboard visualization design

The index was visualized on a choropleth map at the block level, using a four-step sequential color scheme (blue → amber → orange → dark red) to support rapid interpretation during planning exercises (13). Administrative boundaries and ranking information were included to enable users to identify priority geographies and compare vulnerability across districts and blocks.

Choropleth was chosen because officials needed to triage risk across Rajasthan's 352 blocks simultaneously, a task that filled-area encoding supports more efficiently. Continuous raster display was rejected because block-level aggregation does not support the spatial precision that a smooth surface would imply (14). Four color steps preserve the decision relevant ordering without exceeding reliable perceptual limits in field settings (13). The warm-to-red progression aligns with users' intuitive associations with heat risk, reducing cognitive translation during use.

The dashboard also includes separate views for Temperature, Wet Bulb Globe Temperature followed by the composite index, allowing officials to move from climate exposure data they can review intuitively to the index. Selecting a block displayed its vulnerability category, district and state ranking, and domain-specific decomposition, enabling users to identify whether vulnerability was driven primarily by climatic exposure, population sensitivity, or limited adaptive capacity.

2.6 Prototype: Building and Reviewing the Dashboard

A working prototype of the HHVI dashboard was built and reviewed with district officials across 4 districts prior to statewide deployment. Prototype review sessions focused on usability, interpretability, and relevance to existing planning workflows.

Officials confirmed that the integrated vulnerability display was aligned with known patterns within their districts and provided a more comprehensive view of heat-health risk than any individual information source. However, it also consistently surfaced a gap that the prototype displayed vulnerable blocks but did not provide guidance regarding appropriate response actions, making it insufficient for action.

To address this gap, an additional feature termed "Spark Action" was developed. Spark Action links each block's vulnerability grade to predefined response protocols from the state's formal Heat Action Plan (15). When a high-vulnerability block is selected, it surfaces the corresponding protocol steps by health system level: community worker, facility, and district. The feature does not generate new guidance and instead surfaces existing protocol commitments that were previously disconnected from the data showing where they were most needed. The integration framework makes it possible to link vulnerability evidence to operational action while the Spark Action makes that link visible in the dashboard.

2.7 Test: Participatory Deployment through Statewide Workshops

Following prototype refinement, the HHVI dashboard was deployed through a series of participatory workshops conducted across all administrative divisions of Rajasthan between March and April 2026. The workshops served both as a capacity building activity and as a real-world evaluation of the dashboard's usability, interpretability, and relevance to heat-health planning.

A total of seven workshops were conducted, covering 44 districts and engaging 129 government health officials (Additional Information 1). Participants were selected based on their operational roles within Rajasthan's heat-health preparedness and response system. District heat-health nodal officers participated from each district. Block Chief Medical Officers (BCMOs) were selected from blocks identified as highly vulnerable to facilitate discussion of block-level vulnerability patterns and intervention needs. District data managers responsible for routine heat-health reporting were nominated by nodal officers due to their role in data collection, reporting, and interpretation.

Each workshop followed a five-stage process: (1) officials surfaced the heat challenges most pressing in their district; (2) the vulnerability framework was introduced using block-level data from participating districts; (3) officials navigated the dashboard hands-on, reviewing block rankings against ground level knowledge; (4) current gaps in heat-illness recognition and response were mapped; (5) each district team produced a draft Heat Season Plan identifying priority blocks, target populations, and assigned actions. (Additional Information 2)

The participatory workshop format was designed to evaluate whether vulnerability information was understandable and actionable within routine planning processes while simultaneously generating feedback to refine the dashboard and associated decision support features. Insights emerging from these workshops informed final modifications to the dashboard prior to statewide implementation.

2.8 Workshop Evaluation and Statistical Analysis

To evaluate changes in participants' understanding of heat-health vulnerability concepts and interpretation of HHVI outputs, surveys were administered immediately before and after each workshop using Google Forms. Given the relatively small number of participants and the implementation focus of the workshops, all attendees were invited to complete both assessments. Surveys were made available in both Hindi and English, allowing participants to complete the assessment in their preferred language.

The evaluation instrument consisted of seven knowledge and planning-orientation questions administered in both the pre- and post-workshop surveys (S4 Table). These questions assessed participants' understanding of heat-health vulnerability concepts, identification of vulnerable populations, interpretation of HHVI outputs, and approaches to heat preparedness planning. In addition, four post workshop feedback questions assessed participants' perceptions of the workshop's relevance, clarity, and applicability to their professional responsibilities.

Of the 129 officials who attended the workshops, 113 completed the pre-workshop assessment and 108 completed the post-workshop assessment. To assess within-individual change, responses were matched using a hierarchical procedure based on role and district affiliation. Only complete matched survey pairs were included in the primary analysis. Responses with missing data or without a corresponding matched survey were excluded.

The primary outcome measures were changes in the proportion of participants selecting the correct response for each knowledge and planning item between the pre- and post-workshop assessments. Secondary outcomes included participant-reported confidence in applying heat-health vulnerability concepts and perceived usefulness of the dashboard and workshop activities.

Changes in paired categorical responses were evaluated using McNemar's test with continuity correction. Statistical significance was assessed using a two-sided alpha level of 0.05. All analyses were conducted in Python using the SciPy statistical package (SciPy v1.x). Descriptive statistics were used to summarize participant characteristics and workshop feedback responses.

3. Results

3.1 Human-centered design findings

The five-stage human-centered design process generated a series of design insights that progressively shaped the Heat-Health Vulnerability Index (HHVI). Each stage identified an operational constraint encountered by frontline health officials and informed a corresponding design decision. The key findings and resulting design decisions from each stage are summarized in Table 3 and further elaborated in the results.

Table 3. Operational insights generated through the human-centered design process and their translation into HHVI design decisions

HCD Stage	Key design insight	What was learned	Resulting design decision

Empathize: Field scoping	Districts planned heat preparedness using fragmented systems (IHIP, HMIS, NCD, CHIP) and reported heatstroke cases despite recognizing underreporting. Officials repeatedly requested a way to identify *where* vulnerable populations were located and *which departments* should respond.	Operational problem	Established the need for an interoperable block-level vulnerability framework integrating multisectoral data.
Define: Co-design	Officials conceptualized vulnerability as the interaction of climate exposure, health sensitivity, and adaptive capacity, and required outputs aligned with administrative planning units.	Mental model of vulnerability	Structured the HHVI around three vulnerability domains and administrative block-level visualization.
Ideate: Framework	Climate, health, and socioeconomic datasets differed in spatial identifiers, reporting cadences, and geographic resolution, preventing integrated block-level analysis.	Technical interoperability problem	Harmonized 21 indicators from multiple data systems to a common administrative block geography through an interoperable integration framework.

Prototype: Solution	Officials could identify vulnerable blocks but required guidance on translating vulnerability insights into preparedness actions.	Decision-support problem	Developed the **Spark Action** feature linking HHVI outputs directly to State Heat Action Plan protocols and operational recommendations.
Test: Workshops	Officials validated dashboard outputs against local knowledge and used HHVI to identify priority blocks and develop targeted district heat action plans.	Operational adoption	Finalized HHVI as an operational decision-support system embedded within existing government heat preparedness workflows.

3.2 Integration Reveals Block-Level Vulnerability Across the State

Integration of climate, demographic, health, and adaptive capacity indicators produced a statewide Heat-Health Vulnerability Index (HHVI) for all administrative blocks in Rajasthan. The resulting analysis revealed substantial geographic variation in vulnerability across the state, with high- and very high-vulnerability blocks distributed across multiple regions rather than concentrated within a single geographic cluster.

Importantly, vulnerability patterns were often heterogeneous within districts. Blocks classified as high or very high vulnerability frequently occurred within districts that appeared only moderately vulnerable when assessed using district-level indicators. This finding indicates that district-level aggregation may obscure localized concentrations of vulnerability that become visible through block-level analysis. Decomposition of the HHVI further demonstrated that vulnerability emerged through different combinations of exposure, sensitivity, and adaptive capacity factors. While some blocks were characterized primarily by elevated climatic exposure, others exhibited heightened vulnerability due to demographic sensitivity or limited adaptive capacity. Understanding these distinct vulnerability profiles was important for informing context-specific planning responses.

Fig 1 shows the HHVI distribution across Rajasthan. Some of the state's highest vulnerability blocks are embedded in districts whose overall profiles appear manageable.

Fig 2A Rajasthan district-level vulnerability map

Fig 2B Rajasthan block-level vulnerability map

Fig 2 A&B directly illustrates this intra-district heterogeneity by comparing two districts (Jaipur II and Sikar) at both block and district aggregation levels. At the district scale, both appear in the high-risk category. At block level, each contains clusters of Very High vulnerability blocks alongside Moderate blocks, driven by concentrated presence of children, elderly and hypertension patients in specific sub district areas.

Fig 3 The domain decomposition view reveals that vulnerability drivers vary systematically by geography. Western desert blocks show high exposure scores from heat wave frequency and increased driving time to health facilities. But overall vulnerability is driven by a combination of sensitivity and adaptive capacity simultaneously. This multi-causal pattern is not accessible through any single-indicator map.

3.3 The Dashboard as a Decision Support Interface

During statewide deployment, officials used the dashboard to examine vulnerability patterns within their own districts, compare block rankings, and interpret the domain-level contributors to vulnerability. Across workshops, participants engaged most actively when dashboard outputs could be compared against their ground-level knowledge of local populations, occupations, infrastructure, and health system access.

This process provided qualitative validation of the HHVI outputs through comparison with officials' local operational knowledge. Officials frequently identified plausible local explanations for why particular blocks appeared vulnerable, including outdoor occupational exposure, dispersed rural settlements, older health facilities and longer travel times to higher-level facilities. In some cases, officials also identified contextual factors not fully captured by the model, such as seasonal migration patterns, informal work sites, or locally specific community practices. These discussions helped refine interpretation of the maps and demonstrated the importance of pairing quantitative vulnerability outputs with local administrative knowledge.

Fig 4 and Fig 5A&B show the dashboard interface as experienced by officials during workshops. The primary map view (Fig 4) presents the state choropleth alongside a block selection sidebar showing vulnerability grade, district and state rank, and domain score decomposition.

Fig 4: ***Dashboard primary view***

Fig 5A Sidebars with vulnerability grade & rank

Fig 5B Sidebars with vulnerability grade & rank

Fig 5A&B: Sidebar with vulnerability grade, rank, and domain decomposition for a selected block

Dashboard primary view: block-level choropleth with sidebar showing vulnerability grade, rank, and domain decomposition for a selected block. The sidebar is interpretable because the additive index formulation makes each domain's contribution clear and understandable. Contributors to Vulnerability for Kumbhalgarh block of Rajsamand District, where average driving time to facilities equipped to respond to heat stroke cases is over 60 minutes.

Fig 6A Spark Action panel

Fig 6B Spark Action panel

Fig 6A&B: Spark Action panel. Protocol steps from the State Heat Action Plan are organized by health system level (S5 Table) and linked to the primary vulnerability driver for that block, providing targeted actions that the map alone cannot.

3.4 Vulnerability Based Heat Season Planning

A key output of the workshops was the development of draft heat-season plans by participating district teams. To support this exercise, participants were provided with a standardized planning template (S3 Fig) that guided them through identification of priority blocks, vulnerable populations, key drivers of vulnerability, and corresponding preparedness actions.

Using HHVI outputs, district teams identified priority geographies for intervention and developed context-specific response plans. Where alternative priority blocks were proposed (approximately 12% of districts), discussions focused on comparing the dashboard's domain-level contributors with locally observed conditions not captured by the available datasets. This process enabled participants to critically interpret the dashboard outputs, while using the domain decomposition to understand the factors driving vulnerability within the selected blocks. The planning process encouraged participants to prioritize actions based on block vulnerability patterns. Participants used the dashboard to identify both the populations most at-risk and the factors contributing to vulnerability within each priority block.

The resulting plans incorporated both health sector and multisectoral interventions. Health sector activities included targeted ORS distribution, community awareness campaigns, facility readiness assessments, referral preparedness, and outreach to vulnerable populations. Participants also identified actions requiring coordination with other government departments, including water supply management, electricity reliability, urban cooling and greening initiatives, workplace protections for outdoor laborers, and public awareness activities implemented through local administration and education systems. Beyond identifying interventions, workshop discussions also focused on how these activities would be implemented and sustained. Discussions shifted toward embedding accountability within routine processes, including district-level review mechanisms, explicit role assignment, and monitoring of preparedness activities. Officials also emphasized that operational gaps often stemmed from unclear ownership rather than lack of resources, leading to discussions on assigning responsibility for preparedness activities across different levels of the system.

This planning exercise demonstrated that the HHVI could be used to identify vulnerable locations and also to facilitate structured discussions around preparedness priorities and interdepartmental coordination. By linking vulnerability information to specific planning activities, the dashboard provided a practical mechanism for translating risk assessment into operational heat-health preparedness.

Fig 7A Whatsapp message preview in Hindi

Fig 7B **Whatsapp message preview in English**

Fig 7A&B *shows the messages that have been delivered to frontline health workers via*

Whatsapp to address key vulnerability factors including driving time to the health facility and high number of elderly population in the block. The messages are developed in English as well as the local language to ensure ease of understanding and actionability.

3.5 Knowledge and Planning Orientation

Local knowledge validation

Across all seven workshops, the block-level maps were corroborated against officials' ground-level knowledge, and this recognition was, in most workshops, the pivotal moment at which officials shifted from skepticism to active engagement with the tool. Representative examples documented across divisions are included in Table 4.

Table 4. Validation of exposure, health sensitivity, and adaptive capacity indicators by district workshop participants

District	Block	Key Contributors	Corroboration by Officials
Jalore	Agore	High exposure	Plain and dry areas leading to high temperature with a functional river during rainy season
Banswara	Chhoti Sarwan	High Exposure	The recent construction of the power plant has contributed significantly to

			deforestation and high temperatures
Jhalawar	Pirawa	High sensitivity	Lack of doctors in rural areas and due trainings for grassroot workers on recognising early symptoms
Jhunjhunu	Nawalgarh	High sensitivity	Presence of a large number of cement factories and, as a result, high number of outdoor and migrant workers.
Phalodi	Bap	Low Adaptive Capacity	Limited ambulance availability, poor road infrastructure, and long distances to hospitals delay treatment.
Bikaner	Khajuwala	Low Adaptive Capacity	Block sharing geographical borders with neighboring country

This pattern of local validation with officials articulating the reason the map was correct and, in some cases, extending it with knowledge the index could not capture was observed across all seven divisions. Confidence was established by the moment of recognition and alignment.

Shift in planning orientation

Of the 129 officials who attended the workshops, 113 completed the pre-workshop assessment and 108 completed the post-workshop assessment. After matching pre- and post-workshop responses, 101 complete participant pairs were included in the analysis.

Pre- and post-workshop assessments covered seven knowledge and planning items (Table 5). Statistically significant improvements were observed on three items. The largest gain was on the conceptual definition of heat-health vulnerability (Q1): correct responses rose from 73.3% (74/101) to 94.1% (95/101), a +20.8 percentage point increase ($p<0.001$). Pre-workshop, 14 officials (13.9%) defined vulnerability as "the temperature recorded in a district" and 10 (9.9%) as "the number of heat stroke cases reported," directly reflecting the proxies that current planning tools tend to reinforce.

The planning prioritization (Q4) showed a comparable shift. Vulnerability-based prioritization increased from 65.3% (66/101) to 83.2% (84/101), a +17.8 percentage point increase ($p<0.001$). Pre-workshop, 24 officials (23.8%) defaulted to case-count-based planning; post-workshop, this declined to 14.9% (15/101). Correct identification of the first step in district heat-season planning (Q7 — identifying high-risk blocks and vulnerable populations) also increased significantly, from 85.1% (86/101) to 94.1% (95/101), +8.9 percentage points ($p=0.027$).

Three items did not show statistically significant change. Correct identification of the HHVI's purpose (Q5) rose from 85.1% to 91.1% (+5.9pp, $p=0.181$). Recognition of factors increasing block-level vulnerability (Q6) rose from 92.1% to 98.0% (+5.9pp, $p=0.077$), approaching but not reaching significance. Identification of vulnerable populations (Q2) showed a modest, non-significant increase from 93.1% to 96.0% (+3.0pp, $p=0.371$). Correct identification of the most urgent heat-related illness (Q3) was high at baseline and showed a slight, non-significant decline from 87.1% to 84.2% (−3.0pp, p=0.606), consistent with no systematic effect in either direction on this item.

Among the three largest designation groups within the matched cohort, the planning prioritization shift was consistent across cadres. District Nodal Officers (n=29) moved from 72.4% to 93.1% on Q4 (+20.7pp); Block Chief Medical Officers (n=28) from 64.3% to 85.7% (+21.4pp); and Data Managers (n=25) from 64.0% to 84.0% (+20.0pp). The vulnerability conceptualization shift (Q1) was largest among Data Managers (60.0% to 92.0%, +32.0pp) and District Nodal Officers (79.3% to 96.6%, +17.2pp).

Table 5. Pre- and post-workshop assessment results among matched participants (N=101). Δpp = change in percentage points. McNemar's test with continuity correction; α=0.05.

Topic	**Pre workshop**	**Post workshop**	**Δ pp improvement**	**P value**
Q1. Definition of heat-health vulnerability	74/101 (73.3%)	95/101 (94.1%)	+20.8	<0.001
Q2. Identification of vulnerable populations	94/101 (93.1%)	97/101 (96.0%)	+3.0	0.371
Q3. Most urgent heat-related illness	88/101 (87.1%)	85/101 (84.2%)	-3.0	0.606

Q4. Planning prioritization with limited resources	66/101 (65.3%)	84/101 (83.2%)	+17.8	<0.001
Q5. Purpose of the HHVI	86/101 (85.1%)	92/101 (91.1%)	+5.9	0.181
Q6. Factors increasing block-level vulnerability	93/101 (92.1%)	99/101 (98.0%)	+5.9	0.077
Q7. First step in district heat-season planning	86/101 (85.1%)	95/101 (94.1%)	+8.9	0.027

Self-reported workshop experience

Among the 101 matched participants, 97.0% (98/101) agreed or strongly agreed that the workshop clearly introduced heat-health vulnerability concepts in the Rajasthan context; 99.0% (100/101) agreed that the framing of vulnerability in terms of exposure, sensitivity, and adaptive capacity was easy to understand; 98.0% (99/101) agreed that discussions helped them recognize the most vulnerable populations in their district; and 97.0% (98/101) reported feeling confident or very confident in applying workshop lessons to their district. Overall, 87.1% (88/101) agreed or strongly agreed that the workshop met their expectations as an initial sensitization; 11.9% (12/101) strongly disagreed, suggesting that some participants expected deeper operational guidance than the introductory format provided.

4. Discussion

4.1 Summary of findings

This study demonstrates that block-level integration of climate, health, and socioeconomic data can support more targeted heat-health planning within government health systems. The HHVI revealed substantial heterogeneity in vulnerability within districts, highlighting priority geographies that would not have been apparent using district-level indicators alone. During statewide deployment, officials used the dashboard to identify vulnerable populations, interpret the drivers of vulnerability, and develop block-specific heat-season plans.

The most notable finding was a measurable shift in planning orientation. Prior to the workshops, many participants relied on retrospective case counts as the primary basis for prioritization. Following engagement with the HHVI framework, participants demonstrated significant shifts in planning orientation towards prioritizing interventions based on prospective vulnerability and identifying vulnerable populations and high-risk blocks as the starting point for preparedness planning. These findings suggest that integrated vulnerability information can influence how officials conceptualize and organize heat-health preparedness activities.

The findings extend previous work demonstrating the value of participatory climate services and decision-support tools in public health settings. While earlier studies have focused primarily on risk communication or vulnerability assessment, this study provides evidence that integrated climate-health visualization tools can support operational planning within routine government systems.

4.2 Design process reflections

The five-stage human-centered design process produced several findings that have implications beyond this specific deployment. First, the empathy and define stages revealed that the problem was not primarily a visualization problem but a data integration problem: officials were unable to use existing tools because the data was fragmented across systems with no shared spatial identifier. The visualization is the output of solving the integration problem, not the problem itself. This sequencing of understanding the data landscape before designing the visualization is a replicable principle for any climate-health tool development.

Second, the prototype stage was where the most important design decision emerged. Prototype review was conducted with district officials using live vulnerability data from their own blocks in the context of real upcoming preparedness decisions. Since officials were simultaneously trying to plan with the tool, they surfaced the action gap that would not have emerged in a standard usability evaluation. This points to a broader principle for design processes in institutional contexts: prototype fidelity is not primarily about the quality of the visual artifact but about the authenticity of the use context. A prototype embedded in planning sessions surfaces different and more operationally consequential problems than the same prototype evaluated in isolation.

Third, the test phase confirmed that participatory deployment and evaluation are not inherently in tension. The statewide workshops functioned simultaneously as a design test, generating feedback that informed refinement of the tool, and as a validation exercise, producing evidence of changes in participants' understanding of heat-health vulnerability and planning orientation. Designing deployment as a participatory process rather than a product release generated stronger evidence of operational relevance.

4.3 Three principles for last-mile climate visualization

Over the course of our project, three key principles emerged for visualization of climate risks in the local context. First, granularity must match the user's accountability level. BCMOs hold planning authority at block level. The HHVI operationalizes that at the spatial scale where they can act.

Second, credibility in integrated outputs is established through local knowledge validation. Officials engaged most deeply with the dashboard when they could compare outputs against their operational knowledge. Maintaining visibility of exposure, sensitivity, and adaptive capacity components allowed users to interpret vulnerability patterns and assess whether outputs aligned with local conditions. The workshops provided an opportunity for district and block officials to assess, interpret, and contextualize dashboard outputs through discussion of their own operational experiences.

Finally, our findings suggest that the effectiveness of climate decision-support systems depends not only on generating accurate vulnerability assessments but also on embedding those assessments within existing institutional workflows. Throughout the workshops, discussions rapidly shifted from identifying vulnerable blocks to assigning responsibilities, coordinating across departments, and determining how preparedness activities would be monitored through routine review mechanisms. This reflects a broader challenge in climate services: many dashboards successfully improve situational awareness but remain disconnected from the operational processes through which government agencies allocate resources, assign accountability, and track implementation. By linking vulnerability assessments directly to existing Heat Action Plan protocols, the Spark Action feature demonstrates one approach to integrating climate information into routine governance rather than treating visualization as the endpoint of decision support (16).

4.4 Scalability

Although developed for heat-health planning, the underlying integration framework is not specific to heat-related risks. Within Rajasthan, the same spatial backbone and interoperable data architecture have already been adapted to develop an Air Pollution Vulnerability Index, demonstrating the feasibility of extending the approach to other climate-sensitive health conditions.

Many low- and middle-income settings face similar challenges with data fragmentation across government programs and agencies. Where common administrative geographies and data sharing partnerships exist, the framework presented here may offer a practical pathway for translating distributed datasets into operational planning tools.

Scalability depends on three conditions: availability of interoperable administrative datasets, stable administrative boundaries, and institutional ownership of planning processes. While these conditions were present in Rajasthan, implementation in other settings may require additional investments in data governance and interdepartmental coordination.

Future applications should evaluate how the framework performs across additional climate sensitive health risks and governance contexts, as well as its ability to support routine decision-making beyond pilot deployment settings.

5. Strengths and limitations

This study has several strengths. First, the HHVI was developed and evaluated through a participatory process involving government officials across all administrative divisions of Rajasthan, providing statewide representation and ensuring alignment with existing planning structures. Second, the dashboard was deployed within routine government capacity building activities rather than a research environment, allowing assessment under realistic implementation conditions. Third, the paired pre- and post-workshop design enabled measurement of changes in vulnerability conceptualization and planning orientation among participating officials, establishing a baseline against which future longitudinal evaluations can assess whether these shifts are sustained and translate into operational decision-making.

The limitations include the evaluation of immediate changes in knowledge and planning orientation following workshop participation rather than changes in operational decision-making, resource allocation, or health outcomes. The evaluation instrument was developed specifically for this implementation context and not externally validated. In addition, outcomes relied partly on self-reported responses and workshop based planning exercises, which may not fully reflect real world decision-making under operational conditions.

The HHVI uses relative vulnerability classification based on statewide quartiles. Consequently, vulnerability categories represent relative prioritization within Rajasthan and should not be interpreted as absolute measures of risk. This study evaluated operational usability and implementation rather than predictive validity of the vulnerability index. The objective was to determine whether integrated vulnerability information could be understood and incorporated into routine planning processes by frontline health officials. Future work will evaluate the association between HHVI classifications and subsequent heat-related morbidity, mortality, and resource allocation decisions.

A longitudinal follow-up study tracking actual block prioritization decisions, heat season plan implementation, and heat-related illness outcomes is underway and will be reported separately.

6. Conclusion

As climate change intensifies heat-related health risks, public health systems require tools that can translate increasingly complex data into actionable planning intelligence. This study described the development and statewide deployment of the Heat-Health Vulnerability Index (HHVI), a block-level decision-support system that integrates climate, health, and socioeconomic data to support heat-health preparedness for 80 million people in Rajasthan, India.

The study began in a context where routine surveillance often reported few or no heat-related cases, leaving officials with little evidence to prioritize interventions beyond generic seasonal preparedness activities. By integrating multisectoral data into a single block-level vulnerability framework, the HHVI revealed substantial heterogeneity in vulnerability within districts, enabling officials to identify priority geographies, understand the factors driving vulnerability, and tailor preparedness activities accordingly.

Among officials who participated in the workshop, vulnerability-based planning prioritization increased by 17.8 percentage points, while reliance on case-count-based prioritization declined, indicating a measurable shift from retrospective surveillance toward prospective risk-based planning. Workshop discussions also demonstrated that participants viewed the dashboard not as a replacement for local knowledge but as a tool to strengthen it—refining vulnerability assessments, assigning responsibilities, embedding heat preparedness into routine review processes, and identifying opportunities to improve the underlying model over time.

Beyond heat-health planning, the study highlights a broader challenge facing climate adaptation efforts: valuable climate, health, and demographic data often exist but remain fragmented across programs and institutions. The contribution of the HHVI lies not only in vulnerability assessment but also in demonstrating how interoperable data systems, participatory design, and planning-oriented visualization can provide a practical pathway for translating fragmented information into operational decision support. As climate-sensitive health risks continue to grow, approaches that connect integrated data to frontline decision-making may become increasingly important for strengthening local adaptation and public health resilience.

The next phase of this work will focus on three directions. First, a longitudinal study tracking actual block prioritization decisions and heat-season outcomes will determine whether the planning shifts documented here translate into real-world impact, and where the index and underlying model need to be strengthened. Second, Spark Action features will be deepened: as officials use the tool across seasons, the protocol recommendations will be refined into more targeted, data-driven guidance. Third, while the HHVI was designed within the climate and health program, future work aims to integrate vulnerability analysis into broader public health program planning so that climate risk informs routine decisions across maternal health, NCD management, and other existing programs rather than being treated as a separate vertical.

By enabling governments to identify vulnerability before cases emerge, interoperable decision-support systems such as the HHVI provide a practical pathway from reactive surveillance toward anticipatory climate adaptation.

Authorship

Nymisha Herrera Nimmagadda: Conceptualization, Methodology (program design & government integration), Project administration, Writing original draft. Saket Kumar: Methodology (data integration framework, modeling & AI/ML systems), Software, Formal analysis, Data curation, Writing review & editing. Dr. Haya Khan: Conceptualization, Methodology (policy engagement & workshop facilitation). Dr. Narottam Sharma: Conceptualization (state program anchoring), Resources, Supervision (Government of Rajasthan), Dr. Dishani Gupta: Research & Implementation (workshop & field implementation), Editing. Dr. Ruchit Nagar: Conceptualization, Supervision (strategic advisory), Funding acquisition, Editing.

Conflict of Interest

Khushi Baby is a not-for-profit organization with a formal partnership with the Department of Medical, Health and Family Welfare, Government of Rajasthan covering the programs described in this paper. The authors declare no financial conflict of interest. Workshop assessment data were collected and analyzed independently of organizational performance reporting.

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Supporting Information

S1 Fig: Scoping Questionnaire

S1 Table: Source of contributing indicators for HHVI

S2 Table: List of Indicators

S2 Fig:

Fig S2A: Exposure: Correlation and PCA loadings

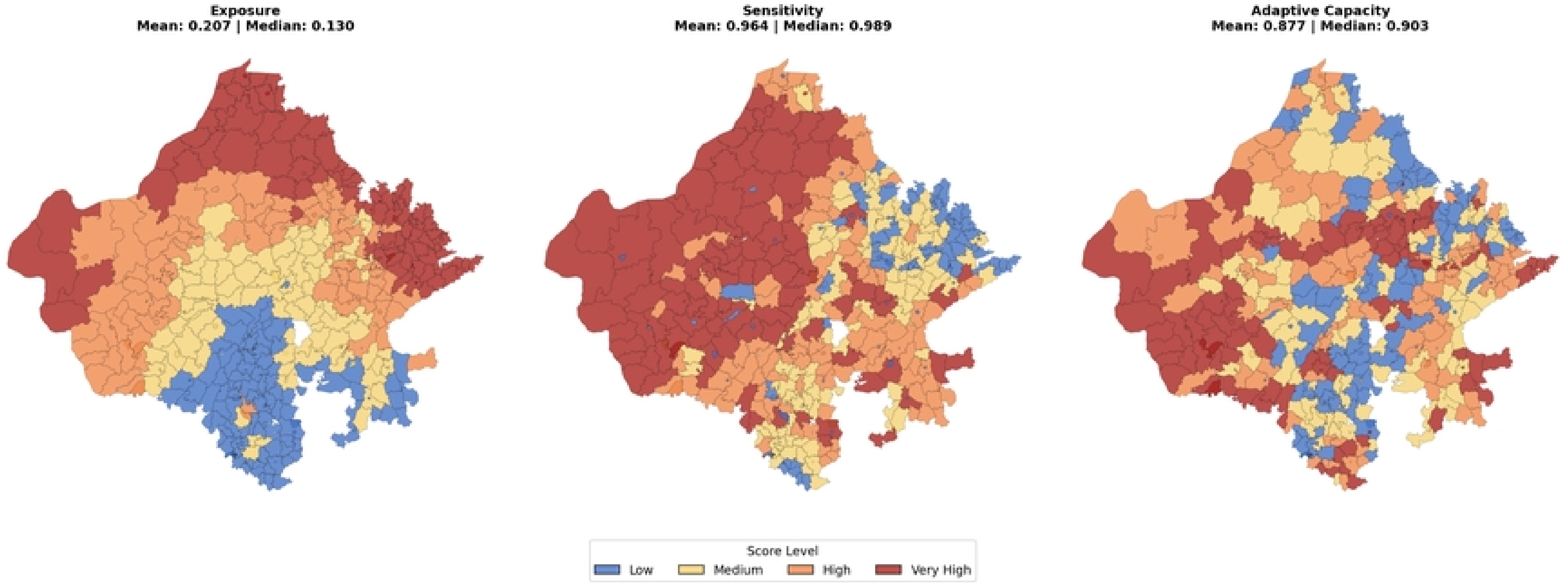
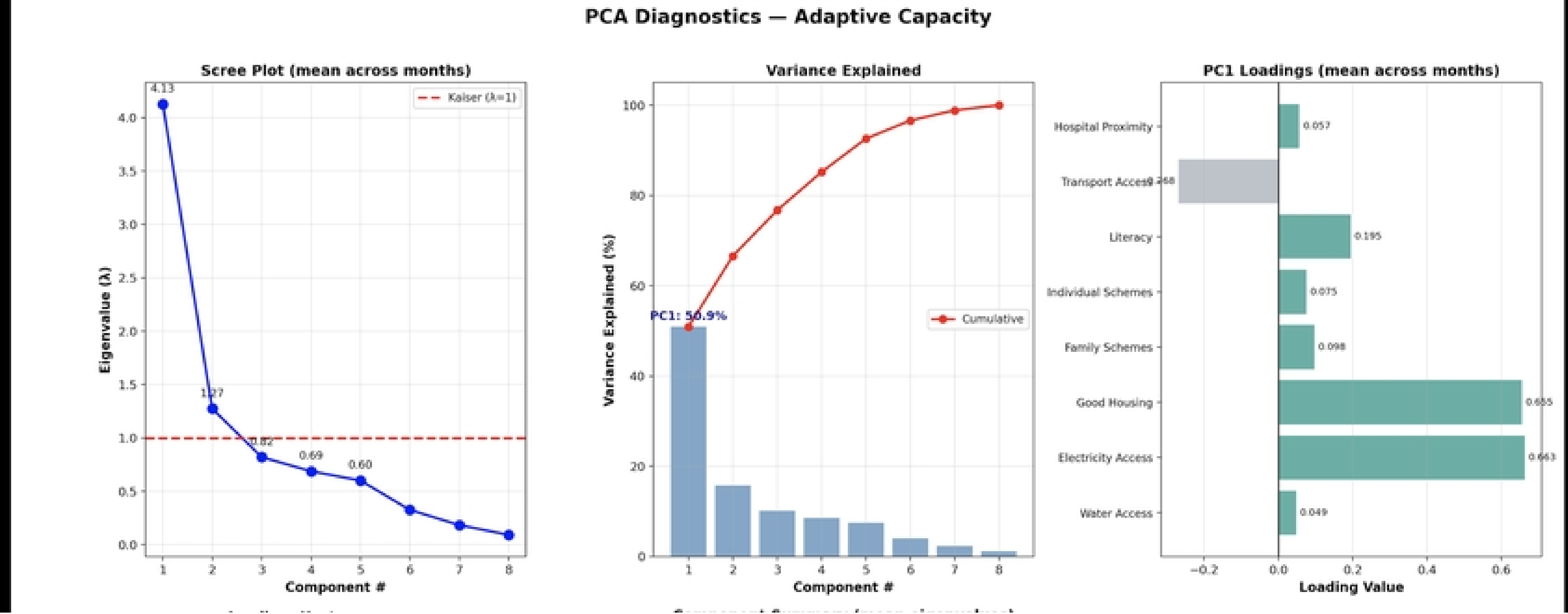
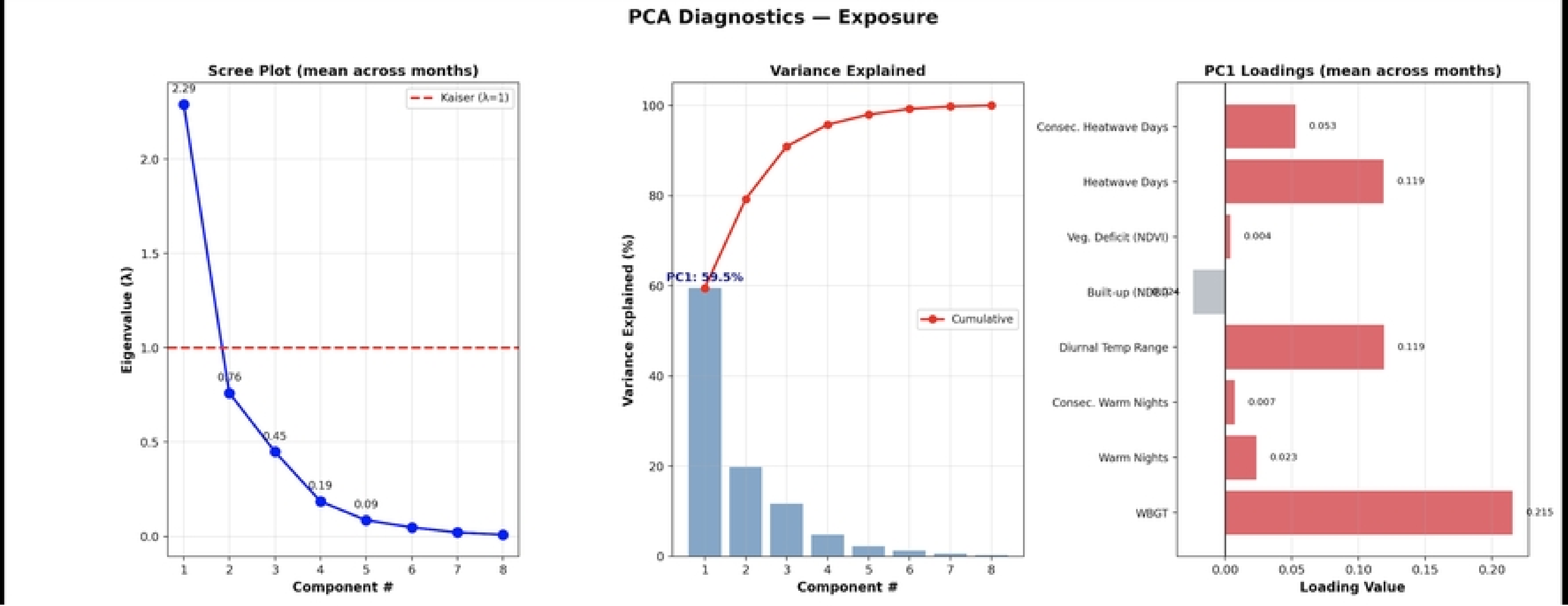


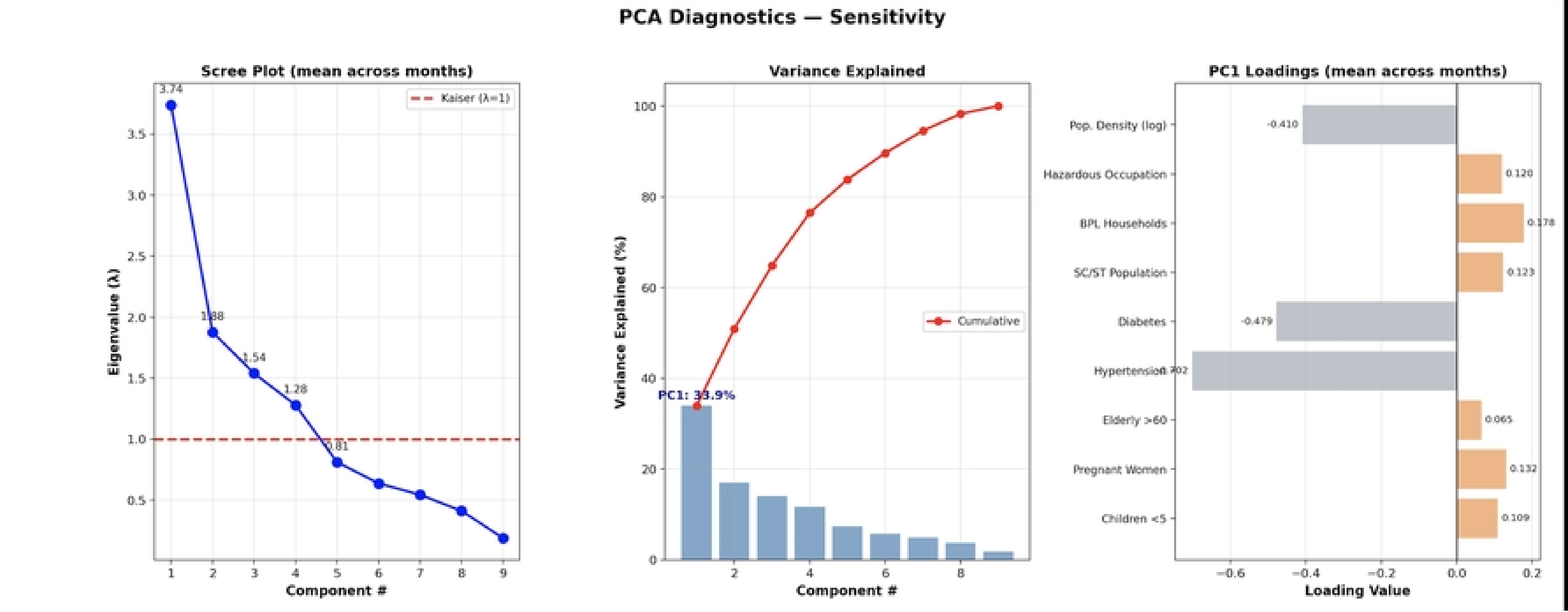
Fig 3 Domain wise decomposition



S2C Fig Adaptive capacity



S2A Fig Exposure



S2B Fig Sensitivity

RAJASTHAN 2026 HEAT-HEALTH VULNERABILITY AND PLANNING WORKSHOP - HEAT SEASON PLAN

District Name:

Top 2 Vulnerable Blocks:

Block Name	Vulnerable Group	Actions	Responsible Department	Timeline

S3 Fig District Heat Season Plan

Khushi Baby Heat-Health Vulnerability Index
Scoping Questionnaire

District Administration *(District Collector, Chief Medical Health Officer, Deputy CMHO):* Engage to understand district-level planning processes, data use, and coordination across departments during the heat season.

- Have you observed an increase in heat-related cases in recent years, and how is this tracked at district level?
- Which blocks or populations within your district appear most affected by extreme heat?
- What data or information do you currently use to make preparedness and resource allocation decisions before and during the heat season?
- What data systems do you currently use for health planning, for example, IHIP, NCD registers, PCTS? Do you ever use them together, or are they consulted separately?
- If you wanted to identify the five highest-risk blocks in your district for heat preparedness, what information would you use and where would you find it?
- How are heat preparedness responsibilities coordinated across departments at district level?

Block Chief Medical Officers (BCMOs): Engage to understand sub-district planning, local vulnerability knowledge, and the gap between available data and operational decision-making at block level.

- Which villages, communities, or occupational groups in your catchment are most affected by extreme heat?
- What factors make them more vulnerable? For example: distance from facilities, water scarcity, housing type, underlying health conditions
- When you plan for the heat season, what is your primary source of information about which communities to prioritize? Is it based on last season's cases, your own field knowledge, or something else?
- What is your escalation pathway when you observe a spike in heat-related cases? Who is informed and within what timeframe?
- If a tool showed you a map of your blocks ranked by vulnerability, combining climate, health, and socioeconomic data, would that change how you allocate resources? What would make you trust or distrust such a ranking?
- What does a useful planning tool look like for you in practice something you consult weekly, seasonally, or only when an alert is issued?
- What data or information would help you better target your preparedness activities?

Frontline Workers *(Community Health Officers, Auxiliary Nurse Midwives, Accredited Social Health Activists)*

Engage to understand community-level vulnerability patterns, household coping practices, and the reach of existing heat preparedness guidance.

- What factors contribute to their vulnerability — type of work, health conditions, age, living conditions?
- When you receive a heat alert, what specific actions are you expected to take? Is it clear to you what to do and for whom?
- Are there households you visit more frequently during the heat season based on your own judgment? What makes you prioritize them?
- What changes do households make to cope during heat events like altering work schedules, resting in shade, increasing water intake?
- What advice do you personally give to high-risk households during heat alerts?
- What would make it easier for you to act quickly when a heat alert is issued?

S1 Fig Scoping Questionnaire

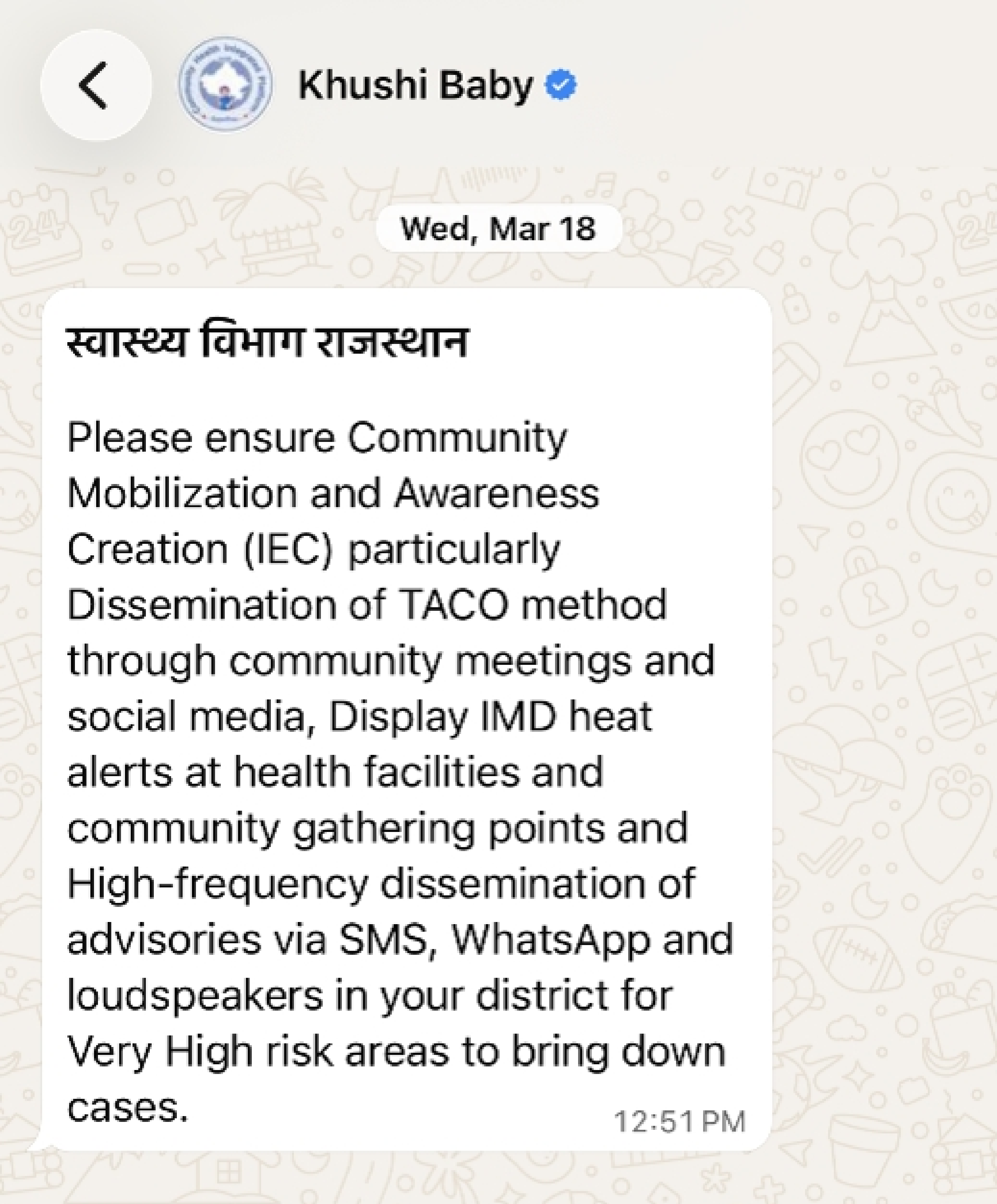


Fig 7B WhatsApp message preview in

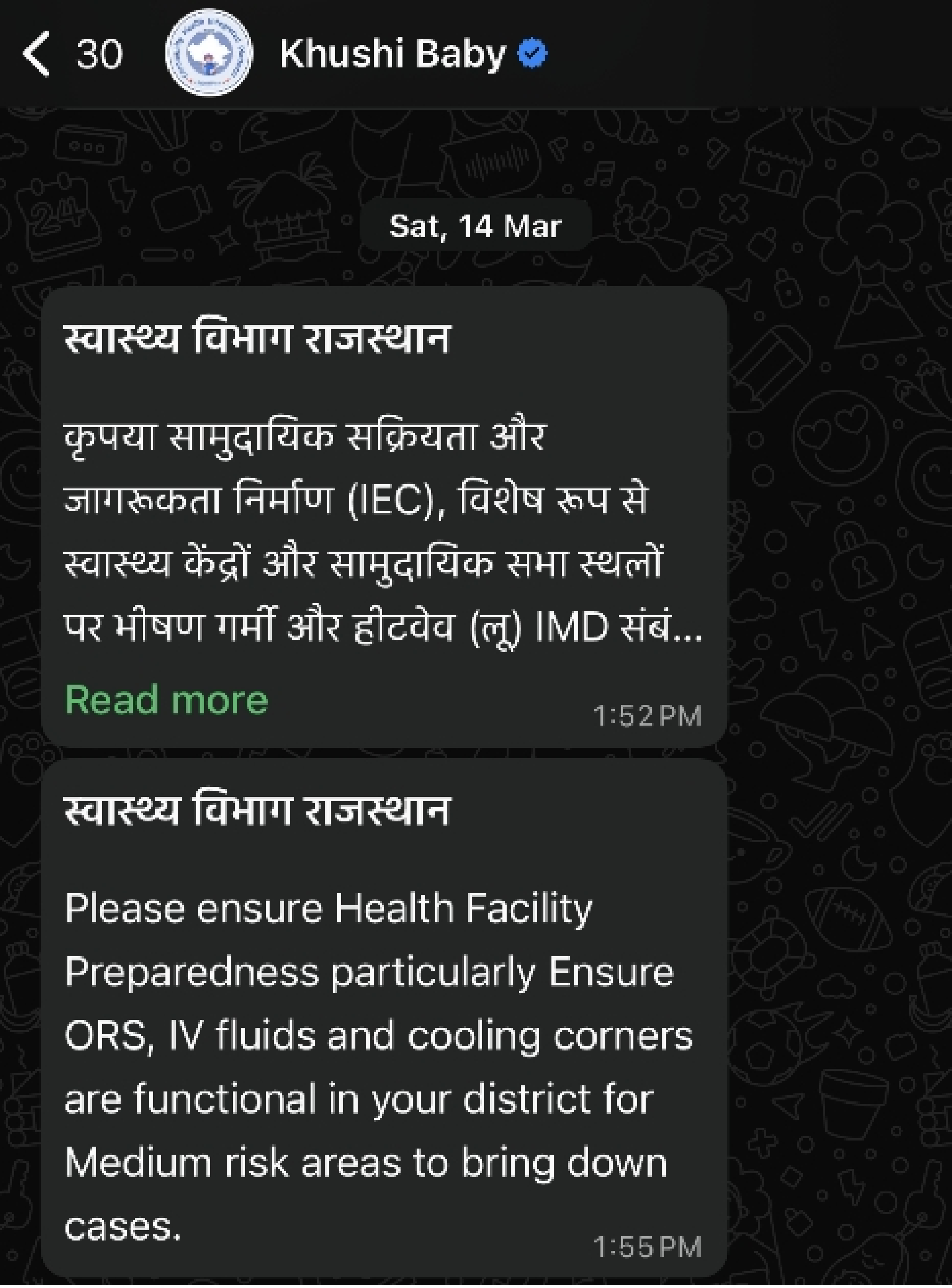


Fig 7A WhatsApp message previe

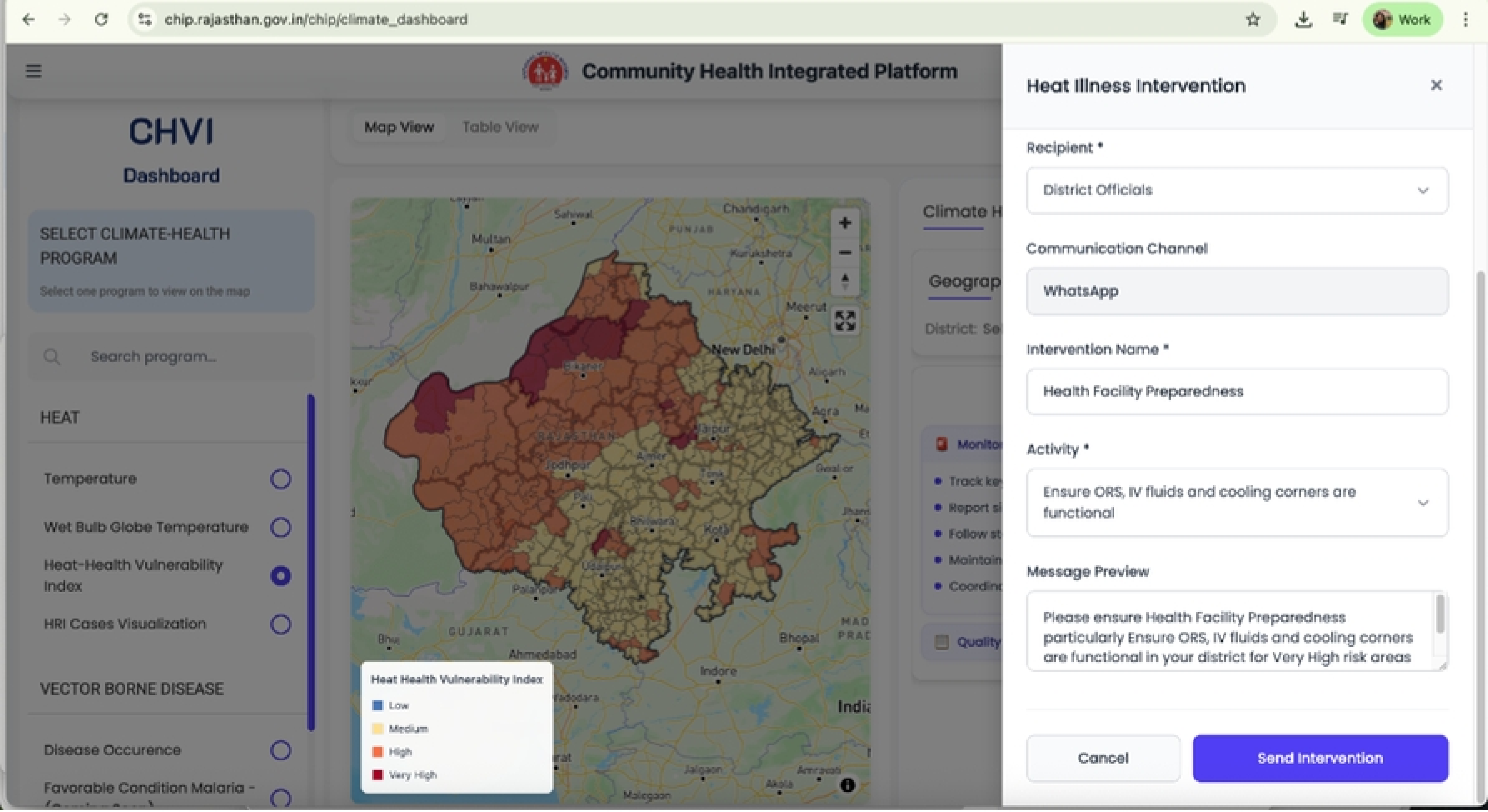


Fig 6B Spark Action Panel

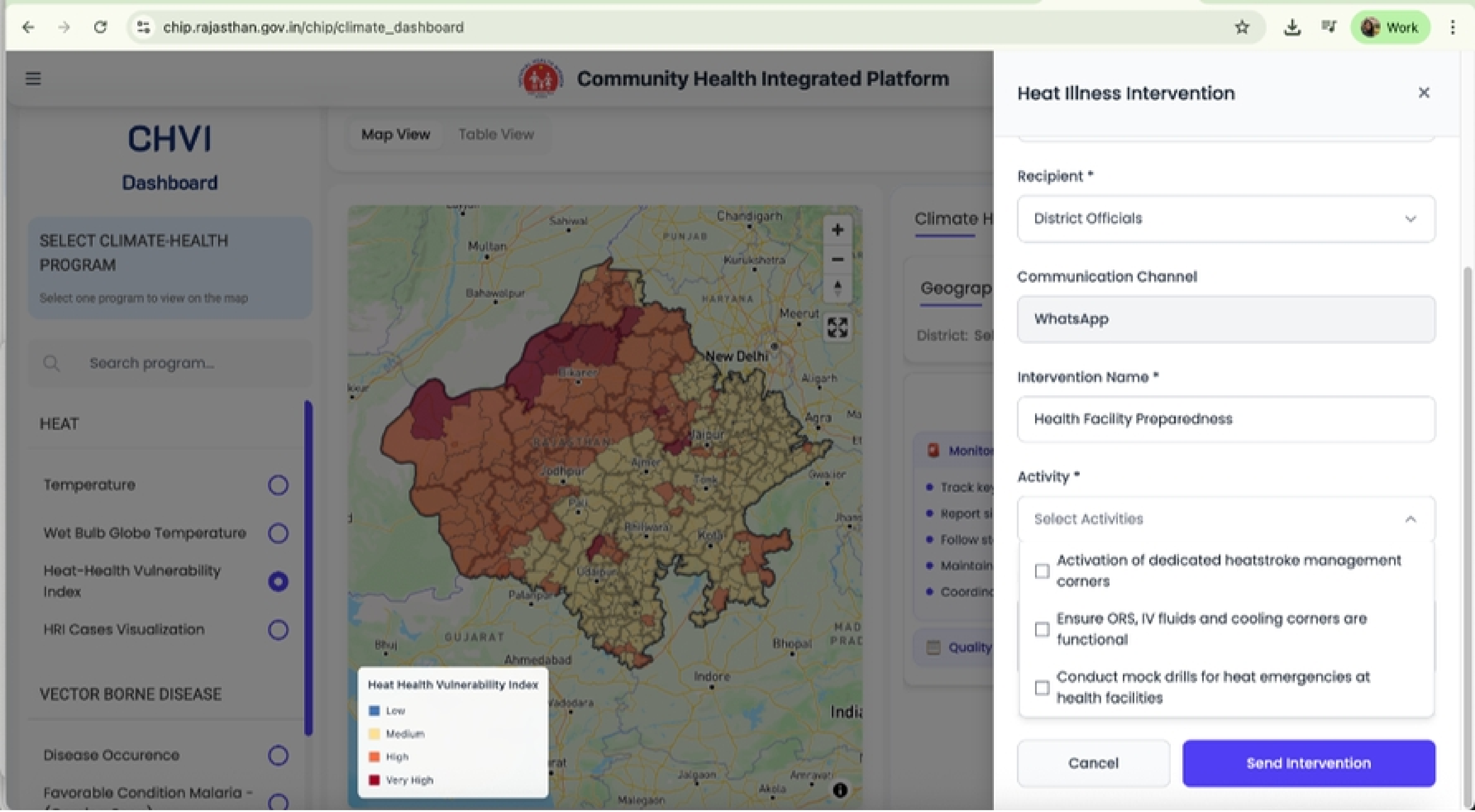


Fig 6A Spark Action Panel

Potable Water Access (%) Water access is critical for hydration during heat exposure.	55.4	358
Stable Electricity (%) Electricity enables cooling devices reducing heat stress.	72.06	389
Thermally Safe Housing (%) Durable housing moderates indoor thermal exposure.	70.63	389
Family Scheme Coverage (%) Social safety nets enhance household resilience.	15.58	315
Individual Scheme Coverage (%) Individual entitlements support personal adaptive capacity.	7	305
Literacy Rate (%) Literacy improves awareness and uptake of heat advisories.	33.79	389
Heat-Safe Mobility Access (%) Transport access facilitates mobility to cooling or care.	33.12	46
Hospital Proximity (driving time) Shorter travel time improves access to heat-related treatment.	-63.35	274

Fig 5B Sidebars with vulnerability grade & ra

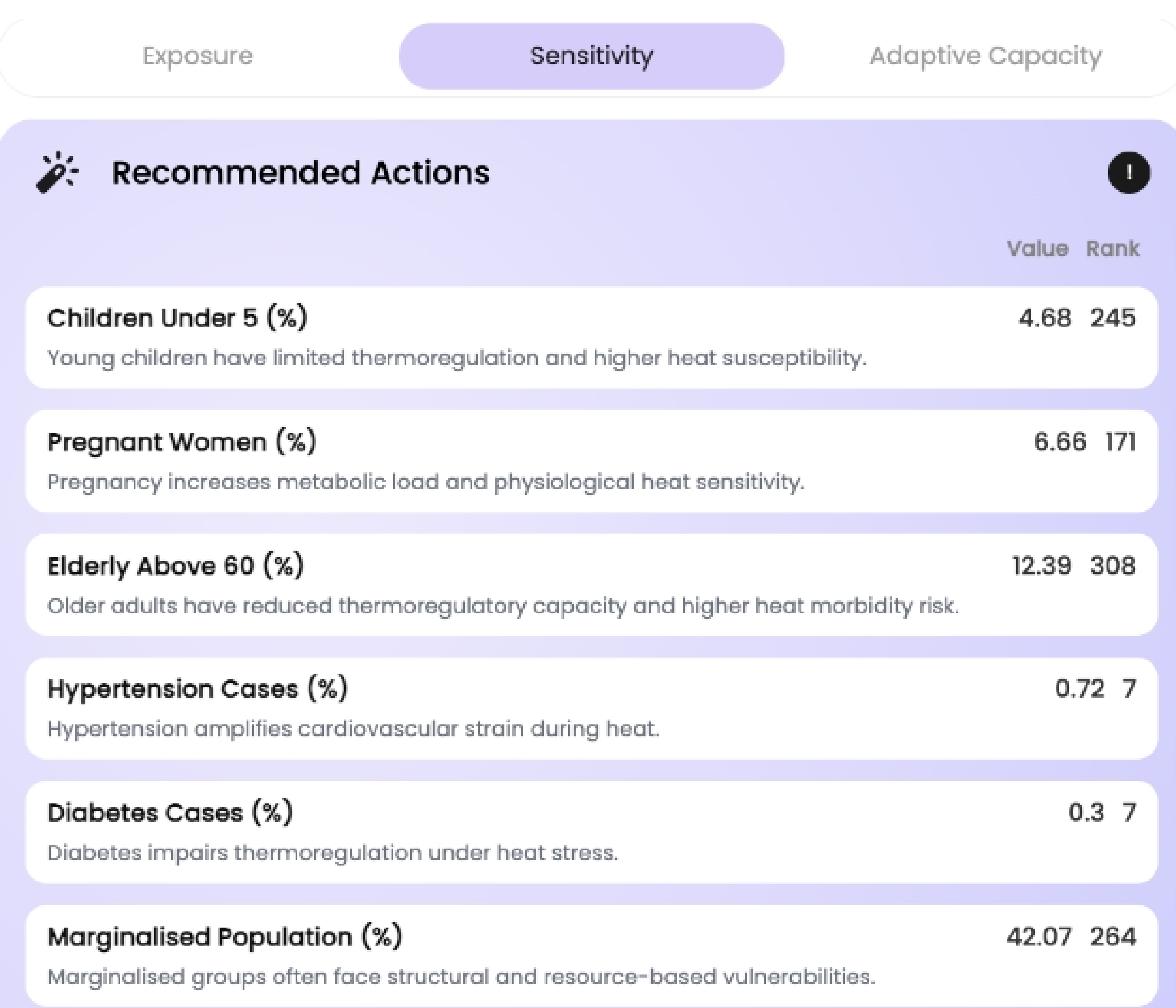


Fig 5A Sidebars with vulnerability grade & ran

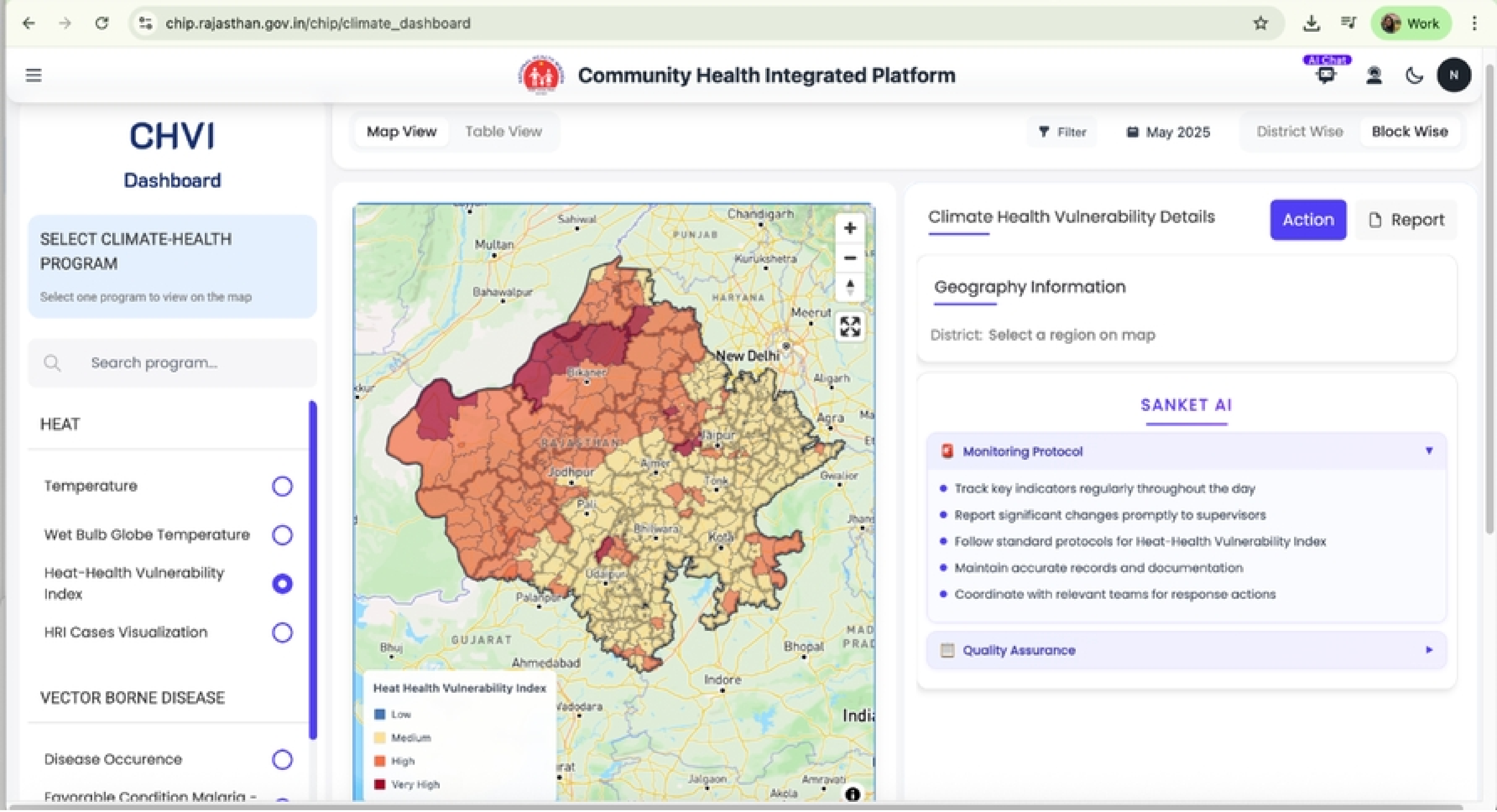


Fig 4 Dashboard primary view

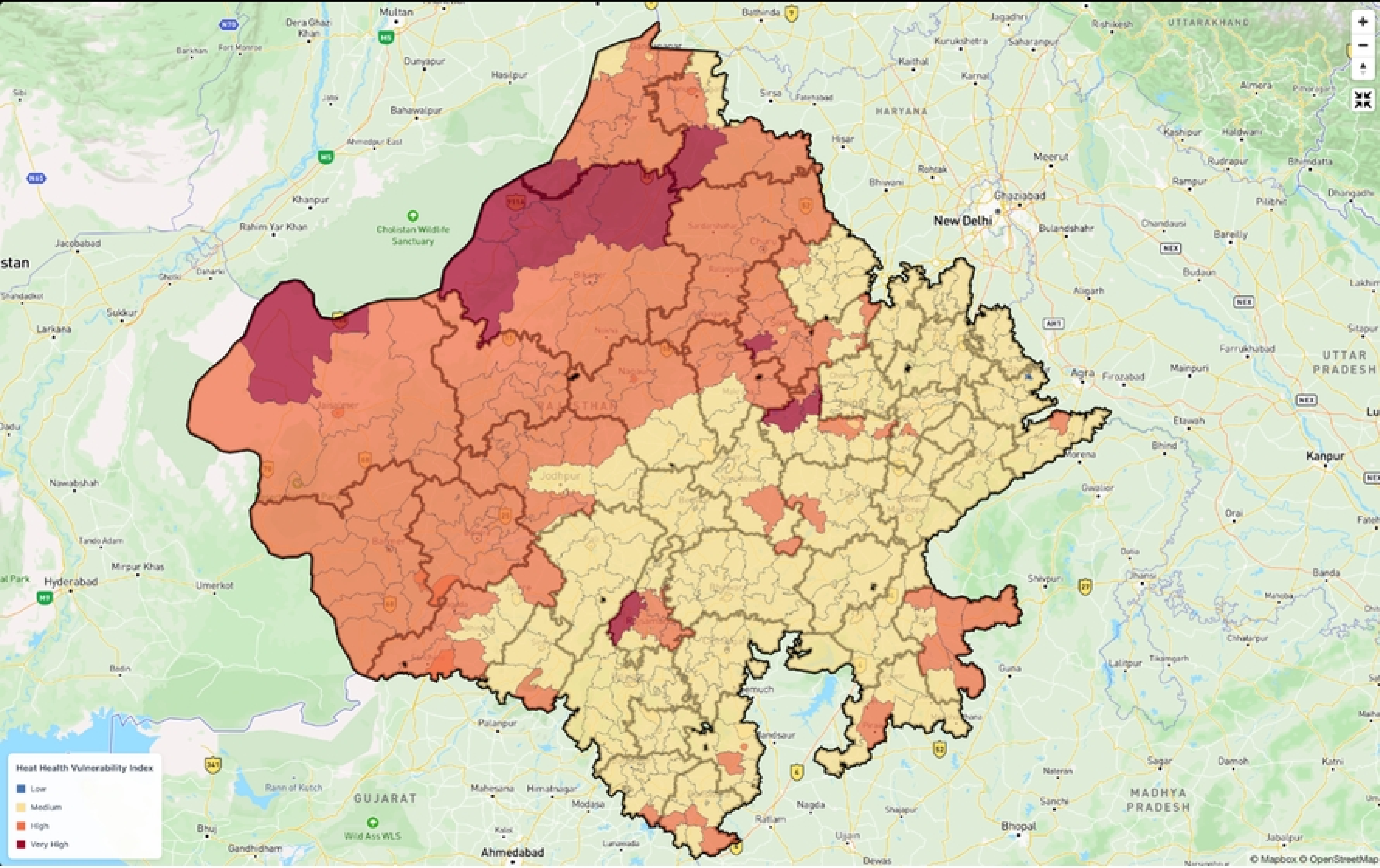


Fig 2B Rajasthan block level vulnerability

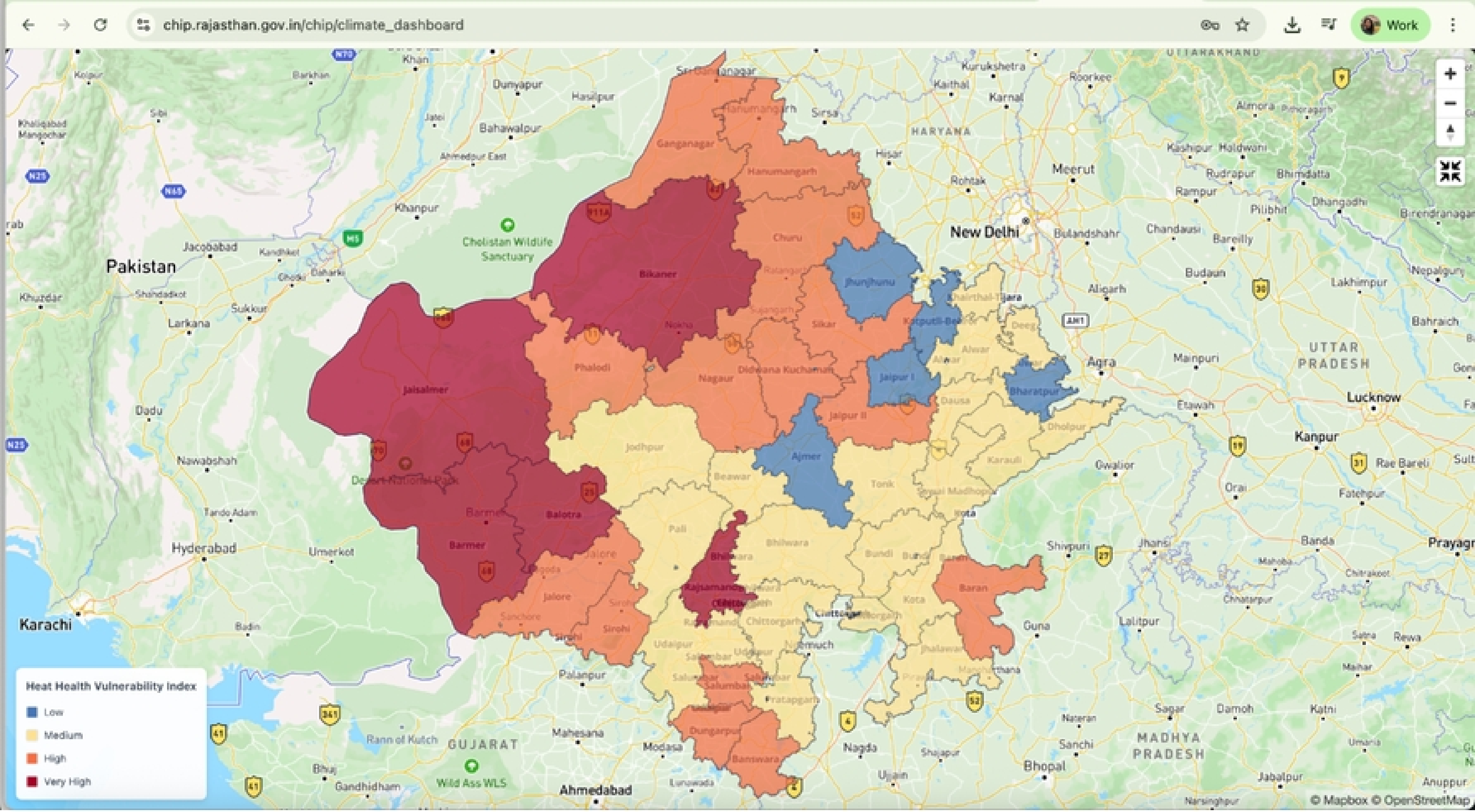


Fig 2A Rajasthan district level vulnerability

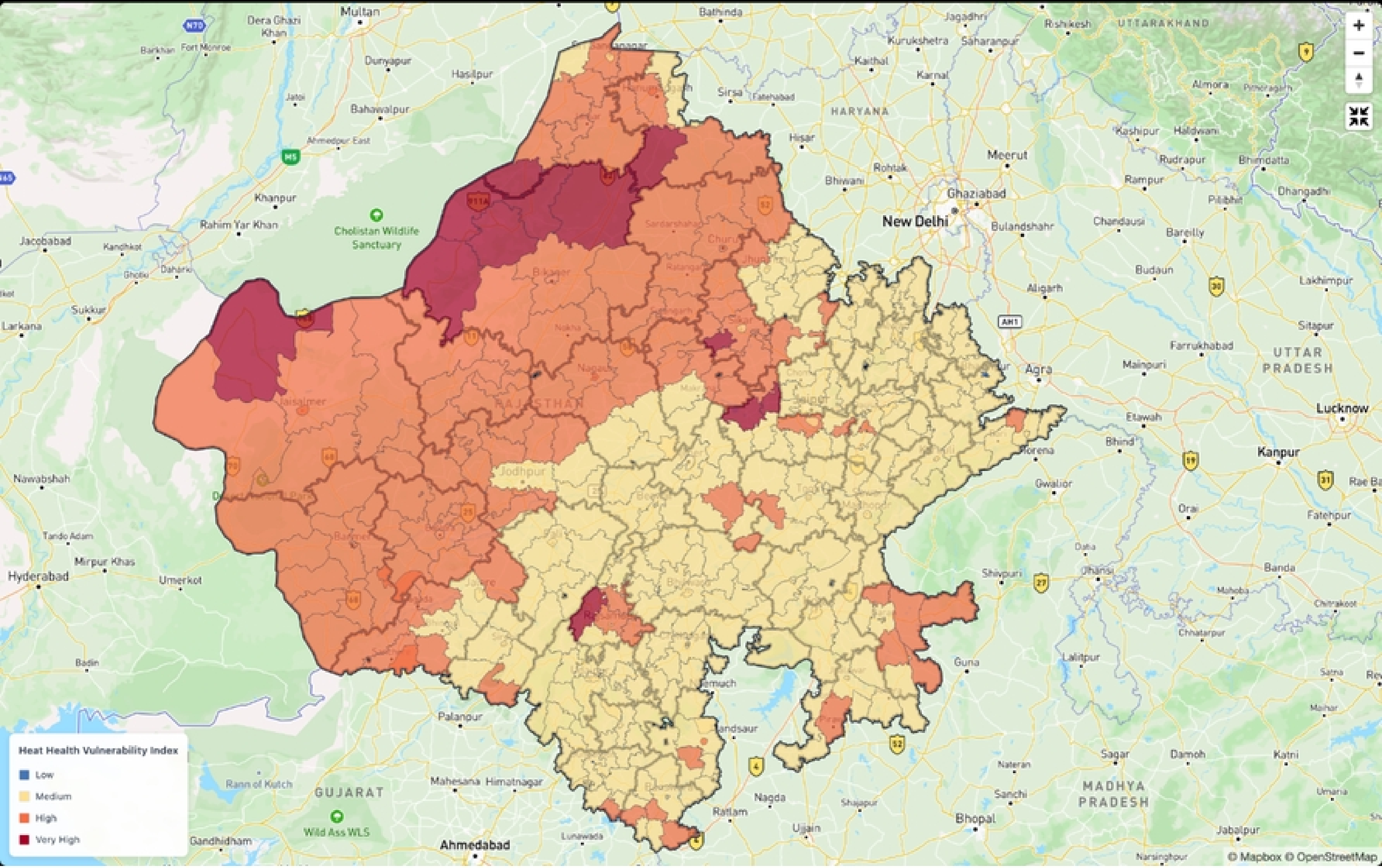


Fig 1 HHVI distribution across Rajasthan