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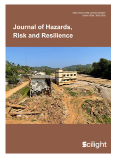

Article

From Individual Agency to Community Resilience: Modelling the Effectiveness of Women-Led Co-Learning Spaces on Climate Action in Jodhpur Using Agent-Based Simulation and Interpretive Structural Modelling

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Abstract: The semi-arid urban settlement of Jodhpur, India, stands at a critical juncture where rapid urbanization and climate change threaten its historic resilience mechanisms. This study investigates the efficacy of immersive workshops conducted in co-learning spaces as vehicles for decentralized hyperlocal climate governance and action. Specifically, it examines how participants of such workshops can function as agents of change within their larger communities by leveraging the existing social practice of Hathai—informal gatherings where women discuss community affairs. Adopting a computational social science approach, we integrate primary data from 25 women community leaders into a stochastic Agent-Based Simulation (ABS) to model the contagion of climate resilience across a synthetic network of 300 community members. Furthermore, Interpretive Structural Modelling (ISM) is employed to map the hierarchical causalities between cognitive and behavioural metrics. Our results reveal a significant paradox: while Climate Knowledge acts as the fundamental structural driver (Level 1) of the resilience ecosystem, it exhibits the lowest transmission rate (24.1% gain). Conversely, Action Intent and Confidence demonstrate the highest contagion potential (38.3% gain), suggesting that behavior propagates faster than information in this cultural context. The study illustrates a plausible structural pathway where traditional ecological wisdom serves as a critical linkage, converting abstract knowledge into tangible reductions in social vulnerability indices (SoVI) and enhancements in Sen's capability approach. We conclude that such smaller intra-community groups as decentralized, women-led nodes could be a viable strategy for hyper-local climate action.

Keywords: agent-based simulation; Interpretive structural modelling; women in climate action; contagion modelling for resilience building

1. Introduction

Jodhpur, historically celebrated as the "Blue City" and "Sun City", exists in a precarious ecological balance on the edge of the Thar Desert. For centuries, the city's survival was predicated on a sophisticated hydro-social network involving water-bodies that network of reservoirs and lakes (jheel and talaab), tanks (jhalara), stepwells (bavdi) and wells (kuan, beri and bera), interconnected by an intricate underground system [1] and a cultural ethos of *Sanchay* (conservation/accumulation) [2]. However, contemporary trends indicate a shift from this historic resilience to modern fragility. Exacerbated by heat stress—indicated by the rising number of heatwave days (Figure 1)—and chronic water scarcity, the city faces an existential crisis that technical infrastructure alone cannot solve.

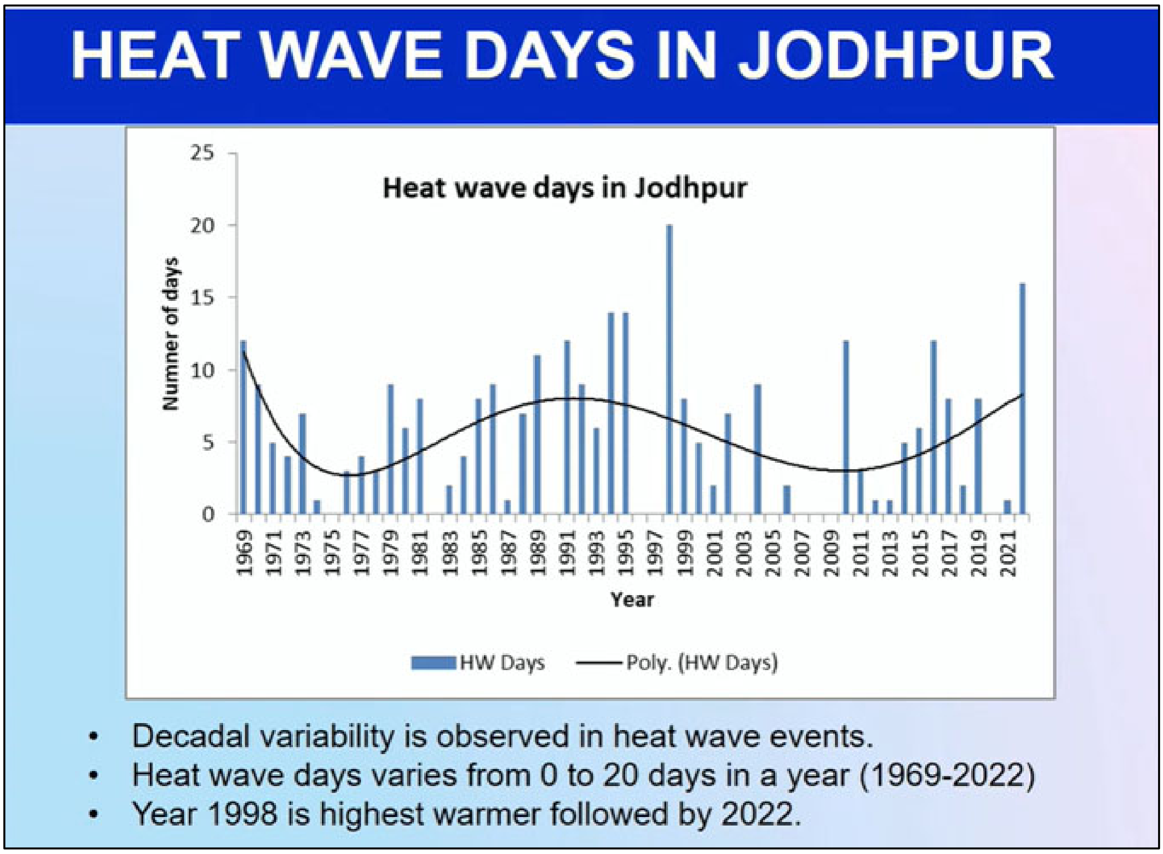

Figure 1. Heatwave days in Jodhpur [3].

This study posits that the solution to this fragility lies in the social architecture of the city itself. We investigate the efficacy of immersive workshops conducted in co-learning spaces, utilizing the participants not merely as students, but as active 'agents of change'. This approach is particularly potent in Jodhpur due to the pre-existing social practice of Hathai—informal, hyperlocal gatherings where community members, particularly women, meet to exchange news and opinions [4].

Historically, Hathai has been an intrinsic part of the socio-cultural fabric of Jodhpur, particularly in the historical areas. Both men and women groups engage in this practice, as goes the folklore. However, like any other practice, Hathai has also experienced an alarming downfall due to the advent of technology-driven engagement tools. Even then, in most of the communities in the old quarters of Jodhpur, Hathai is still prevalent. This study theorises that women-led Hathai can serve as a decentralized node for hyperlocal climate governance and action. If a small cohort of women leaders can be empowered through immersive co-learning, can they effectively "infect" their larger social circles with knowledge and action intent for climate resilience? By channelising these traditional networks, we aim to demonstrate that hyper-local, decentralized climate action is not only possible but structurally superior to top-down mandates in culturally dense environments.

This paper tests the viability of such an intervention using a mixed-method computational framework. We address two primary research questions:

1. To what extent can the agency of a few women propagate through the community to enhance collective resilience metrics via the Hathai mechanism?
2. What is the hierarchical relationship between abstract climate awareness, traditional cultural values, and the tangible reduction of social vulnerability?

2. Background and Literature Review

2.1. The Socio-Ecological Context of Jodhpur

The resilience of Jodhpur is deeply rooted in its place-based wisdom. Study has revealed that the city's traditional architecture and water systems were not merely engineering feats but manifestations of a specific cultural relationship with nature [2] which was and still is extremely necessary for the city's well-being. The desire-based transition to a more modern way of life without paying heed to the existing place-based wisdom has migrated the city to a state of fragility. For example, relying on piped water supply and abstaining from using the historical waterbodies have landed the city in a double jeopardy—there's constant water stress as the piped water supply can't meet the rising demands of the city, which otherwise could have been fulfilled if the historical waterbodies were used and the lack of use and maintenance of the existing waterbodies have led to the precarious rise of groundwater levels, which often times lead to waterlogging, akin to urban floods, whenever there's erratic extreme rainfall events [5]. Additionally, the vernacular architecture of the old city of Jodhpur is more suited to the persistent hot temperatures, making such buildings climate-intelligent and proving its worth as energy efficient [6]. However, the march towards modern style of construction has given way to intense effects of urban heat island, losing the erstwhile benefits of vernacular architecture.

The case of Jodhpur exemplifies that 'Culture for Climate Action' is not about preserving the past in amber but leveraging indigenous logic—such as the thermal comfort yielded by traditional architecture or fostering the use of existing water systems—to inform modern day disaster risk reduction.

2.2. Human Dynamics and Risk Perception

While physical hazards are quantifiable, the human dimension which shapes disaster risk is governed by a complex web of biases, opinions, and cultural constructs. Standard disaster risk management or climate action often assumes a rational actor model, which fails to account for the ambiguity of human behavior in traditional societies.

The theory of bounded rationality notes that individuals make decisions based on limited information and cognitive shortcuts [7]. In Jodhpur, the traditional way of life is not seen as an enabler of climate action. This is a direct consequence of the collective social consciousness, not based on science and evidence. Logically, the communities in the old quarters of Jodhpur should have embraced the vernacular way of constructing homes to suit the effects and impacts of the changing climate but the collective social pull has been towards quick and modern fixes. In fact, the traditional way of life, appropriate for the usual extreme heat, should have been the cornerstone of daily life, however the shift away from it signals that the modern day transformation is not bounded to science and evidence.

Douglas and Wildavsky (1982) [8] argue that risk perception is selected to reinforce the established social structure. In tight-knit communities, risks that threaten social cohesion and persisting social structures are often prioritized over physical risks. This turns out to be true when seen through a socio-cultural lens. The traditional knowledge to moderate the effects of extreme temperature is held by the women of the communities and that is put to practice in everyday life through the domestically exercised food habits or seasonal choices of clothes and even through the tasks performed throughout the day. But this knowledge is largely kept off the records by not adopting them in local policies like the Heat Action Plan. Although women and other such labelled vulnerable groups are included in stakeholder discussions but their generational knowledge is not weaved into the action policy. A plausible reason could be that acknowledging this knowledge would affect the social structure where women are not looked at as leaders and maintaining the social hierarchy is important than facing the effects and impacts of the changing climate together without any gender-based discrimination.

Opposed to the idea of celebrating traditional knowledge and place-based wisdom, is another aspect of romanticising it beyond ends. Communities often exhibit a local invulnerability belief, assuming that their traditional methods will protect them indefinitely, despite changing climatic baselines. Thus, the prospect of blending modern-day science with the existing knowledge to build hyperlocal resilience remains distant in some cases.

Therefore, any effective intervention must navigate these cognitive landscapes, using trusted insiders—women, in this case—to translate external scientific knowledge into internal cultural narratives, in addition to giving space to the actual bearers of traditional knowledge, which could be immensely helpful in climate action.

2.3. Theoretical Frameworks and Research Gap

Existing literature establishes Jodhpur as a historic repository of place-based wisdom, a treasure trove of resilience practices, some of which are held by women in the old city, which are invaluable in this era of the changing climate. These women exercise this knowledge daily—through culinary choices, clothing and domestic resource management—passing it intergenerationally from grandmothers to daughters [5]. Theoretically, they hold the key to hyperlocal climate action. However, a significant gap exists between this potential and the reality of policy and practice.

This gap is defined by three converging problems, as highlighted in the previous sub-section. Neither men nor women fully realize the scientific efficacy of these traditional practices. While women have performed these tasks for years, the lack of scientific validation prevents them from viewing these acts as climate action, rendering the knowledge invisible to the holders themselves (Bounded Rationality). Despite policy documents like the Heat Action Plan, women's generational knowledge is not integrated. As noted in the Cultural Theory of Risk, acknowledging this knowledge might disrupt the established gender hierarchy. Thus, the social structure prioritizes its own maintenance over the functional benefits of women's wisdom. Conversely, there is a danger of romanticizing tradition beyond ends, without filtering it through modern science.

We theorize that if we empower a cohort of women with lucid climate science, validating their traditional knowledge through a scientific lens, they can transcend these barriers. Through their Hathai groups, they can enhance collective resilience by acting as confident agents of change.

To measure this, we adopt two theoretical indices. As proposed by Cutter (2003) [9], social vulnerability is the susceptibility of social groups to harm. We theorize that empowering women decreases Social Vulnerability (SoVI). And, as proposed by Sen (1999) [10] in his seminal Capability Approach, development is the expansion of freedoms. We theorize that validation increases women's 'Capability' to act.

3. Methodology

3.1. Data Collection: The Manthan Workshop & Survey

Primary data was sourced from the Manthan initiative (Figure 2), an immersive workshop series involving 25 women community leaders in Jodhpur. While a sample size of *N* = 25 is statistically small for generalized population inference, it is highly appropriate for Agent-Based Modelling (ABM) calibration [11].

Figure 2. Manthan Workshop.

Contagion modeling studies how something—such as a disease, behavior, opinion, or information—spreads through a population or network of individuals. Traditional contagion models often focus on pairwise interactions, where transmission occurs between two connected individuals, but recent advances emphasize higher-order interactions involving groups, which better capture social contagion processes like opinion formation or behavior adoption [12–15]. In contagion modeling through ABM, the goal is to characterize the Seed Agent. We are not surveying the entire population but we are characterizing the behavioural rules of the influencers. A deep psychometric profile of 25 key leaders is sufficient to seed the simulation [11,12].

More importantly, accessing women in conservative urban pockets for in-depth climate psychology profiling is challenging [5]. This cohort represents a high-quality, purposive sample of change agents, glimpses of which has been captured in Sanchay [5]. Practically, this study models a specific intervention—can empowered women, through Hathai, brin about substantial change in climate awareness, literacy and action. The 25 women represent the actual size of the initial cohort. Scaling the model (as done in the simulation to 300 agents) allows us to project the impact of this specific group without needing to survey 300 non-participants initially.

The survey utilized a 5-point Likert scale to capture three important dimensions as shown below in Table 1. Figure 3 illustrates how the study theorises the selection of these dimensions as suitable for determining the effective transmission of climate awareness, knowledge and intent to act through the Hathai network.

Table 1. Linkages between survey questions and dimensions for the study.

Questions	Factor	Dimension
1.	Perceived knowledge about climate change	Knowledge (K)
2.	Perception of differential impact of climate change on women	
3.	Perception of impact of climate on family	
4.	Perception of impact of climate change on women health	
5.	Perception on culture to be a tool for climate action	Traditional Lifestyle (T)
6.	Perception on participation of women in decision making related to climate action	Action or Intent to act (A)
7.	Perception on efficacy of climate action if women empowered	
8.	Perception about responsibility of government towards climate action	
9.	Perception about responsibility of individual/community towards climate action	
10.	Intent to act	
11.	Age of participant	Age

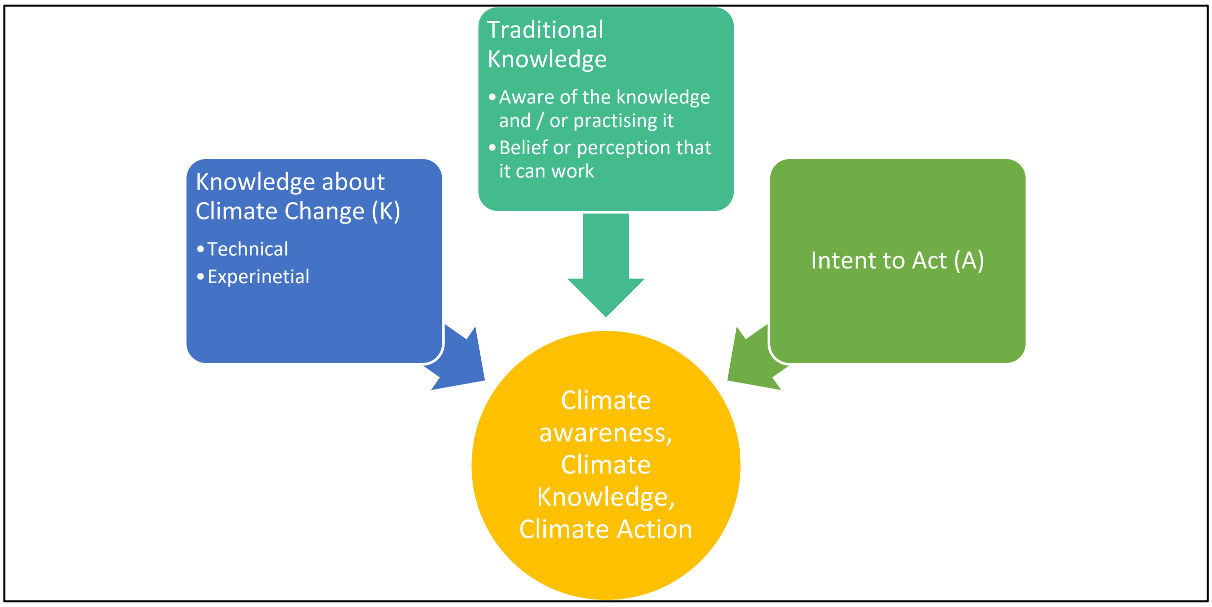

Figure 3. Theorisation of how the dimensions contribute to building hyperlocal climate resilience.

To rigorously quantify the impact of the Hathai intervention, the survey instrument was explicitly designed to map onto the theoretical frameworks identified in Section 2.3. The following mapping was used to derive the simulation parameters as shown in Table 2:

Table 2. Establishing linkages between survey questions, dimensions and frameworks used for resilience metrics.

Theoretical Construct	Component Variables	Corresponding Survey Question	Rationale for Linkage
SoVI Reduction (*Composite Index*)	Knowledge	[1–4]	Vulnerability is reduced when a community understands the hazard (e.g., EWS awareness).
	Traditional Practice	[5]	Vulnerability is further reduced when a community retains indigenous coping mechanisms (Place-based wisdom).
Sen's Capability (*Composite Index*)	Knowledge	[1–4]	Knowledge provides the potential or "freedom" to understand options.
	Action Intent	[6–9]	Intent represents the agency or "functioning" to convert potential into action.

By combining these questions, the study moves beyond simple awareness checking. For example, a respondent might have high Knowledge but low Action Intent, which according to Sen's framework, indicates her Capability is low because she lacks the agency to act. Conversely, high Tradition combined with high Knowledge creates a robust shield against Social Vulnerability.

3.2. Phase 1: Agent-Based Simulation (ABS)

We constructed a stochastic influence diffusion model in R to simulate a "Hathai" network. It is essential to clarify that this simulation is designed as a mechanism-exploration tool rather than a forecasting or predictive model. Its primary purpose is to explore the 'what-if' dynamics of social contagion and the structural viability of the Hathai as a transmission node, rather than to provide precise demographic projections or absolute magnitudes of real-world impact.

3.2.1. Agent Initialization

The simulation environment is populated by a total of 325 (N = 325) distinct agents, categorized into two functional roles designed to mirror the social architecture of the community. Participant Agents (P = 25), representing the women leaders who participated in the immersive Manthan training and survey. These agents are modelled to serve as the primary drivers of social contagion. Their attributes are not randomized but are empirically initialized using direct scores from the Manthan survey. These scores reflect high levels of motivation and pre-existing traditional knowledge, positioning them as hubs of resilience within the network. To address the critical distinction between formal scientific awareness and place-based wisdom, the initialization of General Member Agents (GM = 300) are done. These General Member agents follow a differentiated baseline strategy, where Climate Knowledge (K) is initialized at a low baseline (20–35), which reflects the community's current disengagement from formal climate science and modern EWS (Early Warning Systems) terminology and Traditional Lifestyle and Wisdom (T), initialized at a higher, moderate range (55–70). It is important to note that the 300-agent population is conceptualized here as a stylised construct rather than a literal demographic replica. This approach follows the mediation school of modeling, where the simulation serves as a laboratory to explore 'what-if' scenarios regarding the catalytic power of leaders, rather than providing precise estimates of real-world contagion magnitude.

This differentiation addresses an invisible knowledge theory which posits that invisibility does not imply absence. The higher Traditional Lifestyle and Wisdom (T) baseline acknowledges a deep, existing reservoir of place-based wisdom that remains un-activated in the context of modern climate adaptation. The Participant Agents (P) do not create knowledge from a blank slate, instead, they act as catalysts, using their training to align and activate this latent traditional wisdom (T) with actionable climate intent (A).

3.2.2. Weighted SoVI Influence

Recognizing that community resilience is more heavily anchored in cultural identity than formal science, the influence exerted by a leader on a GM's vulnerability is weighted as follows:

$$\text{Inf\_SoVI} = ((0.3 \times K) + (0.7 \times T))/10;$$

where, by assigning a 70% weight to Traditional Lifestyle (T), the model ensures that the reduction of social vulnerability is driven primarily by the traditional anchor, honouring the community's specific socio-cultural context and the 30% weight to Knowledge (K) acknowledges that while formal knowledge is necessary for modern EWS (Early Warning Systems), it is a secondary driver. It adds flavours to the multi-dimensionality of resilience but does not anchor it.

3.2.3. Network Topology and Social Interaction

The structural arrangement of agents is modelled as a clustered network topology, designed to mirror the decentralized, trust-based architecture of the Hathai. The network consists of 25 discrete social clusters, each centered around a Participant Agent (P) who acts as a local knowledge hub. Each cluster contains 12 General Member agents (GM), forming a small-group environment where neighbourly ties facilitate information exchange. This configuration reflects a decentralized node structure where influence does not flow from a single top-down authority, but rather propagates radially from multiple local leaders simultaneously.

3.2.4. The Stochastic Update Rule for Stylized Deliberation

To avoid the rigidity of deterministic modeling, the agent interaction is framed as a stochastic update rule for stylized deliberation. This rule simulates the consensus-building atmosphere of the Hathai (community gathering). The update for any given General Member metric ($GM_{m(t)}$) follows the logic:

$$GM_{m(t+1)} = GM_{m(t)} + (Inf_P \times (100 - GM_{m(t)}) \times \alpha);$$

where ($100 - GM_{m(t)}$) represents the Growth Potential or the remaining room for improvement, α is the interaction rate (learning rate) and Inf_P is the influence strength of the leader.

The temporal evolution of the community's resilience is simulated over ten discrete time steps, with each step representing a month of social interaction—also representative of the rough number of months between two successive warm and hot season. The mathematical logic governing this change is a standard learning curve, specifically formulated as a difference equation that models asymptotic growth towards a maximum capacity [12,15]. This approach ensures that while agents can improve significantly, they cannot exceed the theoretical maximum limit of resilience.

The term $GM_{m(t+1)}$ represents the future state, denoting the updated resilience score of a General Member at the next time step. This value is derived from $GM_{m(t)}$, which is the current resilience score of that member. The rate of change is modulated by the learning rate, denoted by α. It is to be noted that rather than a fixed biological constant, α represents the intensity of deliberation. It captures the frequency and depth of conversations within the Hathai. By testing multiple values in a sensitivity analysis ($\alpha = 0.05$ to 0.2), the robustness of the model's core findings (such as the behavioural paradox) are explored.

The force driving this change is I_P, or the Influence Strength. This is a normalized score ranging from 0 to1, derived from the specific attributes of the Participant Agent assigned to the group. This variable acts as a force multiplier; a leader with higher "Action Intent" or "Knowledge" exerts a proportionally stronger gravitational pull on the behavior of her group members. Finally, the term $(100 - GM_{m(t)})$ represents the Adaptation Gap. This component calculates the difference between the maximum possible score of 100 and the agent's current score. Functionally, this introduces the concept of diminishing returns. As a General Member's resilience improves, the gap shrinks, making further marginal gains smaller. This mathematical feature reflects the psychological reality that moving from a poor state to a good state is often faster than moving from a good state to a perfect state.

Interactions are modelled as discrete time steps, where each step represents a cycle of Hathai gatherings. This allows the model to capture the cumulative effect of recurring social practice over time.

While the update logic follows a mathematical curve, it is conceptualized here as a stylized approximation of periodic deliberation. In this framework, the interaction is not a one-time infection of ideas, but a recurring conversational practice. The model collapses multiple, complex ethnographic mechanisms—such as trust-building, repetition, and collective validation—into a simplified, iterative update rule. The functional form of the model represents a leader-weighted peer deliberation. In each time step, the cluster moves toward a new consensus position, guided by the influence of the Participant Agent. This influence is not an artifact of top-down authority but is derived from the leaders' workshop-enhanced confidence and their roles as trusted facilitators.

3.3. Phase 2: Interpretive Structural Modelling (ISM)

To rigorously analyse the complex causal relationships between the cognitive and behavioural factors identified in the simulation—such as knowledge, traditional wisdom, confidence, and action—we employed the structural analysis technique known as Interpretive Structural Modelling. This methodology is designed to establish a hierarchical structure among a set of related variables, revealing the fundamental drivers and dependent outcomes within a complex system [16–18]. It is essential for determining which factors are the root causes of resilience change and which are merely resulting effects.

The first step in this process involved Variable Identification. Seven key metrics, representing the crucial facets of community resilience tracked during the Agent-Based Simulation, were selected as the system elements for the structural analysis. These variables include Climate Understanding, Early Warning System Seriousness (specifically, heatwave early warnings), Traditional Resilience, Action Confidence, Action Taken, Social Vulnerability Reduction, and Sen's Capability. These elements serve as the nodes in the final hierarchical model.

The variables selected for the Interpretive Structural Modelling analysis are comprehensive metrics that collectively describe the progression from abstract awareness to tangible outcomes. Climate Understanding reflects the agent's level of scientific literacy regarding climate change. Early Warning System Seriousness specifically measures the agent's preparedness and behavioural response to immediate threats, particularly heatwave alerts common in Jodhpur. Traditional Resilience quantifies the conviction that indigenous or traditional practices offer effective coping mechanisms. Action Confidence and Action Taken capture the crucial psychological step from intent to actual behavioural change. Finally, the two top-level system outcomes, Social Vulnerability Reduction (based on Cutter's framework) and Sen's Capability (representing expanded agency and freedom), serve as the ultimate dependent variables for measuring the intervention's success.

Following identification, the core relational step is performed by constructing the Structural Self-Interaction Matrix (SSIM) and then generating the Reachability Matrix. The Structural Self-Interaction Matrix is developed based on theoretical underpinnings and expert judgment, wherein the existence and direction of the relationship between every pair of variables is established. For instance, a directional relationship is assigned based on whether

'Climate Understanding' influences 'Action Confidence'. The Reachability Matrix is subsequently derived from the Structural Self-Interaction Matrix by applying transitivity rules. This mathematical refinement ensures that all implicit, indirect causal pathways (e.g., if A influences B, and B influences C, then A implicitly influences C) are captured, resulting in a comprehensive map of influence within the system.

The final phase of the analysis involves the *Matrice d'Impact Croisés Multiplication Appliquée à un Classement* analysis, often referred to by its French abbreviation—MICMAC. This analysis categorizes the identified variables based on their driving power (the total number of variables they influence) and their dependence power (the total number of variables that influence them). Plotting these two powers on a coordinate system results in four distinct clusters: (1) Autonomous Variables, which have weak driver and dependence power; (2) Dependent Variables, which are highly influenced by others but have little influence themselves; (3) Linkage Variables, which are highly influential and highly dependent, making them unstable but crucial pathways; and (4) Driver Variables, which possess high driving power and low dependence, identifying them as the most fundamental elements of the system. This clustering process provides the final, layered hierarchy presented in the results.

4. Results

4.1. Simulation Dynamics (Agent-Based Simulation): The Contagion of Resilience

The Agent-Based Simulation provides a temporal window into how the Hathai, functioning as a decentralized node network, serves as a transmission engine for climate resilience attributes across the community.

The simulation of ten interaction cycles reveals a gradually increasing but eventually diffusing curve across all variables, a pattern consistent with Rogers' Diffusion of Innovations theory [19], as seen in Figure 4. There is an evident initial of social friction, or the initial resistance of the General Member agents to adopt new behaviours or information, reflecting the necessary warming up period for trust and credibility to be established within the Hathai groups. This is followed by a rapid increase phase across all metrics, where the rate of change accelerates significantly, indicating the community has begun to adopt. At this stage, the combined influence of the 25 Participant Agents is sufficient to overcome the baseline inertia, and the positive feedback loop of social adoption begins. The final phase, depicts a flattening (saturation), reflecting diminishing returns as the General Members' scores begin to align closely with the high initial capabilities of the women leaders.

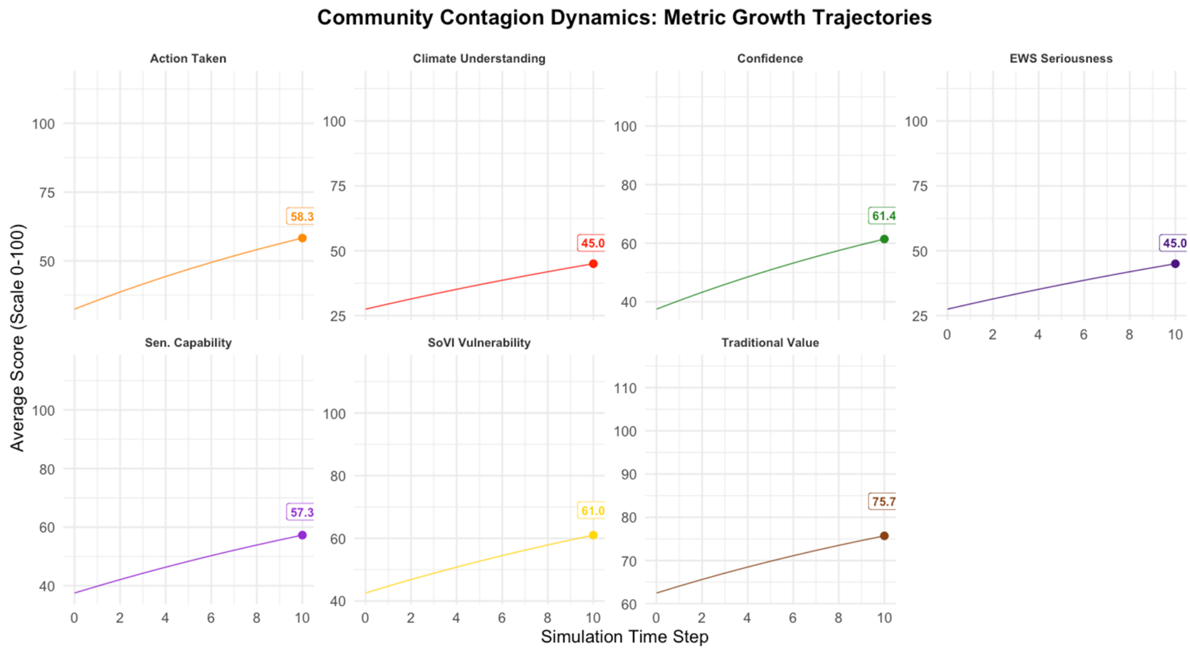

Figure 4. Contagion Dynamics over Time.

Quantifying the total system gain over the simulation period reveals a critical divergence in the infectiousness of different attributes, as depicted in Figure 5. The highest percentage gain was recorded in the behavioural and psychological variables—"Confidence in Action" (38.3% increase) and "Action Taken". Conversely, the cognitive variable, "Climate Understanding", exhibited the lowest overall gain at 24.1%. This empirically demonstrates a significant paradox. The Hathai is approximately 1.6 times more effective at generating confidence and behavior than it is at propagating complex, technical climate knowledge. This suggests that the primary mechanism of change is one of Social Proof [20]—members are copying what trusted, empowered leaders do, resulting in faster behavioural adoption, rather than first requiring an in-depth scientific understanding of the underlying threat.

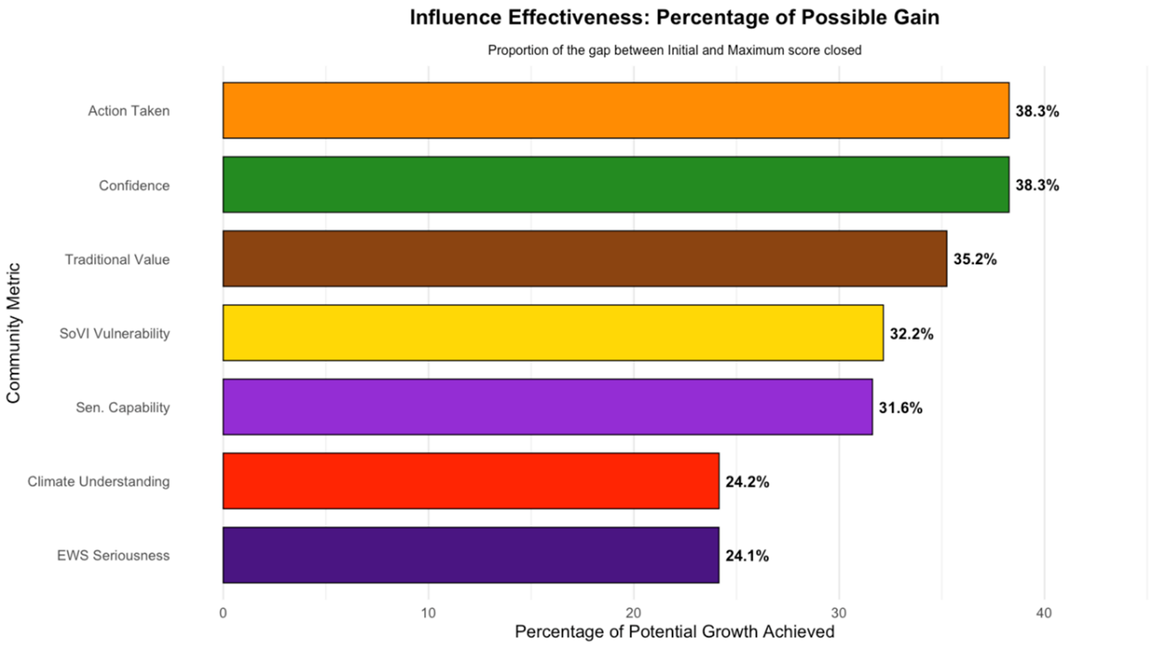

Figure 5. Final Effectiveness (Percentage Gain).

4.2. Sensitivity Analysis: Validating the Behavioral Paradox

To ensure the robustness of the simulation results and address potential concerns regarding parameter dependency, a Sensitivity Analysis was conducted on the interaction rate (α). The primary objective of the sensitivity analysis in this study is to determine whether the observed behavioural paradox—wherein behavioural contagion consistently outpaces cognitive knowledge gain—is an artifact of specific parameter selection or a fundamental structural property of the modeled Hathai network. Following the principles of mechanism-exploration, this analysis shifts the focus from absolute magnitudes (the specific percentage of gain) to the robustness of relative ordering (the hierarchical relationship between variables).

The interaction rate (α) was selected as the primary independent variable for sensitivity testing, as it represents the frequency and intensity of social deliberation within the Jodhpur community. We employed a One-at-a-Time (OAT) sensitivity approach, varying α across a spectrum from 0.05 (representing casual, infrequent social contact) to 0.2 (representing intensive, daily community engagement). This range encompasses the plausible variations in how often women might engage in Hathai discussions post-workshop.

As illustrated in the simulation runs (Figure 6), increasing the interaction rate (α) leads to a non-linear increase in the absolute gains for all metrics. For instance, at $\alpha = 0.05$, the net gain in Action Intent was +14.2, whereas at $\alpha = 0.2$, it surged to 42.3. However, across all 1000 Monte Carlo iterations for each parameter set, the relative hierarchy of transmission remained invariant. Regardless of the speed of social diffusion, Action Intent and Confidence consistently maintained a 1.4× to 1.6× lead over Climate Knowledge. This stability indicates that the model is parametrically robust. The higher contagion potential of behavioural metrics is not dependent on how often people talk, but rather on the initial social capital and trust indices derived from the Manthan survey data.

The interpretive role of this analysis is critical as it validates that the simulation is not a black box forecasting tool, but a transparent mechanism for understanding social contagion. By demonstrating that the gap between knowledge and action persists across different interaction intensities, we can conclude that:

1. The behavioural paradox is a structural feature of the network. The existing social practice of Hathai is inherently optimized for the transmission of social proof and peer-led confidence rather than the dissemination of technical scientific data.
2. Local governance strategies should prioritize action-first interventions. Since the model shows that Action Intent propagates more easily than technical knowledge even in low-interaction scenarios, climate resilience programs in Jodhpur should leverage behavioural nudges and social imitation rather than relying solely on information-heavy educational campaigns.

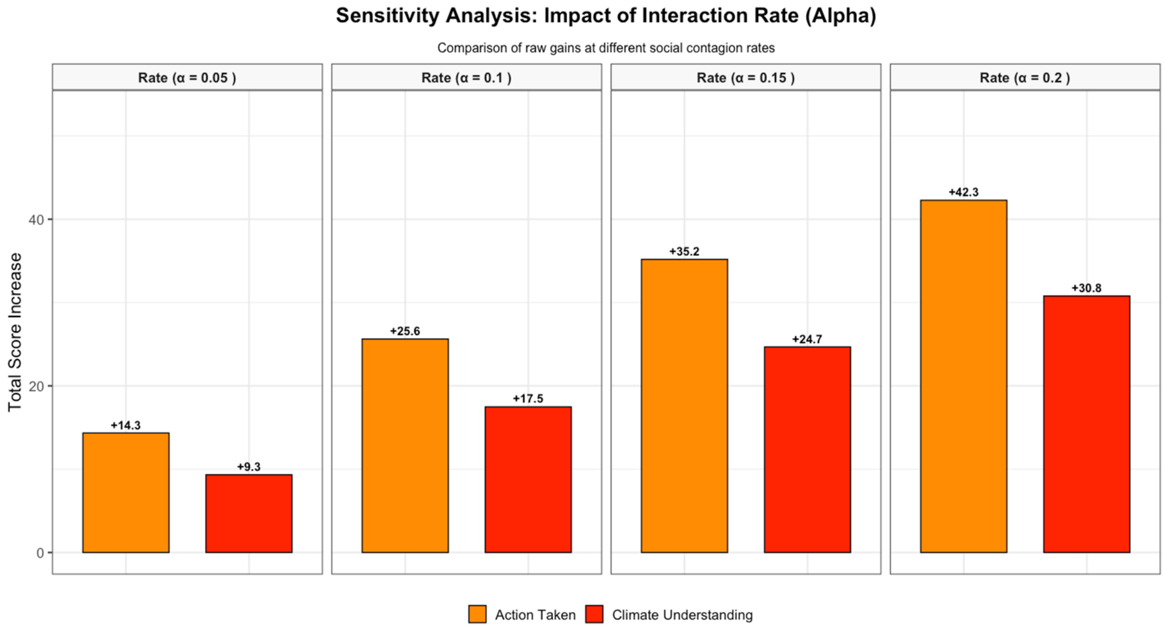

Figure 6. Sensitivity analysis to depict the impact of interaction rate (α).

In summary, the sensitivity analysis confirms that while the absolute magnitude of community resilience is sensitive to the frequency of social interaction, the behavioral-over-cognitive advantage is a stable, reliable mechanism of the Hathai system. This analysis also confirms that in high-trust, place-based social systems, behavioural contagion through trusted neighbourly ties functions as the primary mechanism for community adaptation. Community members are more likely to adopt the actions of a respected peer leader via trust and imitation before they fully internalize the complex scientific knowledge justifying those actions. This reinforces the model's status as a data-driven representation of stylized deliberation rather than a generic mathematical diffusion.

4.3. Structural Hierarchy (Interpretive Structural Modelling): The Architecture of Change

The Interpretive Structural Modelling methodology provides a critical decomposition of the system, revealing a clear causal architecture that governs the transition from abstract knowledge to tangible resilience. By establishing the Reachability Matrix and performing the subsequent MICMAC analysis, the seven variables are clustered into a four-level hierarchy based on their driving power (influence on others) and dependence power (influence received from others).

The hierarchical structure in Figure 7 clearly defines the pathway to resilience across three effective levels:

1. Level 1 (The Foundation—Driver Variables): The variables Climate Understanding and Early Warning System Seriousness are positioned at the base of the hierarchy. By definition within the Interpretive Structural Modelling framework, these are the fundamental structural drivers of the entire system. They possess high driving power but low dependence power, meaning they influence nearly all other variables but are themselves influenced by none of the others. This confirms that while knowledge may be slow to spread, it remains the necessary prerequisite and the most stable leverage point for systemic change, acting as the ignition for the entire resilience ecosystem.
2. Level 2 (The Bridge—Linkage Variables): This level is occupied by Traditional Resilience, Action Confidence, and Action Taken. These are classified as Linkage Variables because they possess both high driving power and high dependence power. They serve as the critical operational bridge between abstract knowledge and final outcomes. The presence of Traditional Resilience at this level is a crucial finding, indicating that the mere existence of cultural practices is insufficient; they must be actively linked with Action Taken and driven by Climate Understanding to become functional.
3. Level 3 (The Outcome—Dependent Variables): The top of the hierarchy is occupied by Sen's Capability and Social Vulnerability Reduction. These are the Dependent Variables and represent the emergent properties of a successful intervention. They possess low driving power but high dependence power, meaning they are the ultimate goals that are influenced by the successful activation of the lower levels (Knowledge and Linkage variables). This structure empirically validates the theoretical assumption that enhancing community agency

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(Sen's Capability) and reducing the susceptibility to harm (Social Vulnerability Reduction, as defined by Cutter) are the logical outputs of targeted behavioural and cognitive interventions.

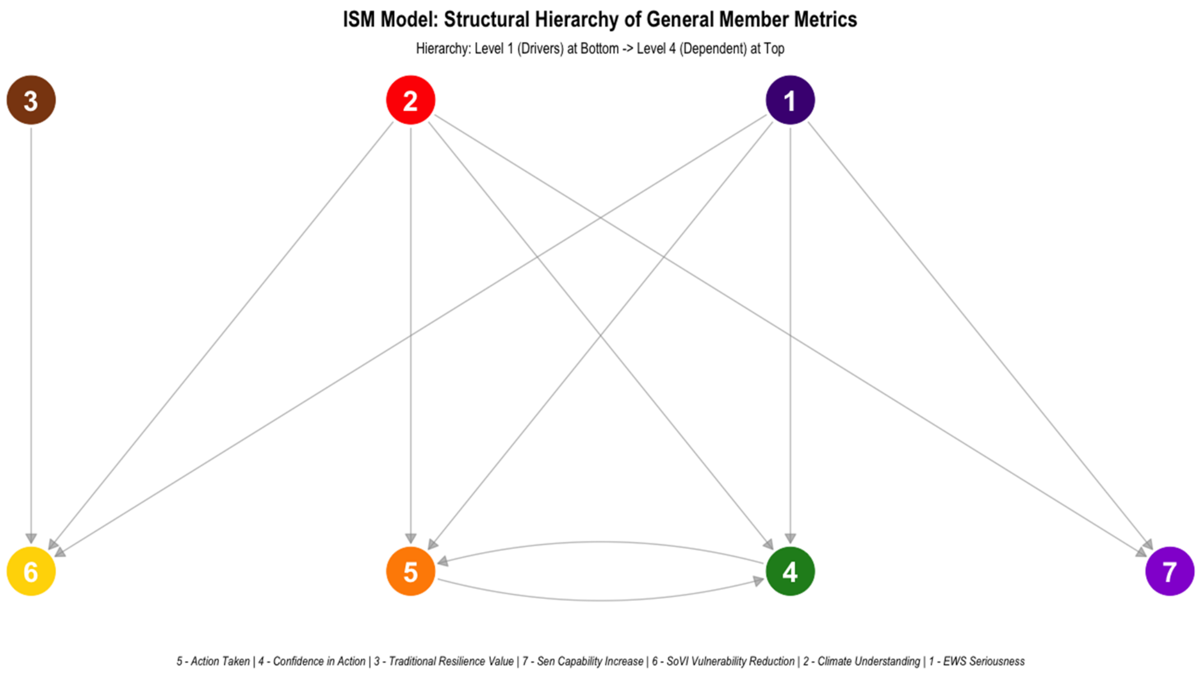


Figure 7. Interpretive Structural Modelling Diagraph (Hierarchical Model).

The MICMAC plot further (Figure 8) clarifies the results. The variables in the Linkage zone (Zone III) are highlighted as being the most volatile. Because they are both highly influential and highly dependent, any disruption in the input flow (e.g., if the women leaders stop receiving or sharing information) would lead to the rapid degradation of these behaviours. This finding strongly reinforces the need for continuous support for the Hathai nodes to maintain the critical Linkage variables (Traditional Resilience, Action Confidence, and Action Taken) that mediate between foundation knowledge and final resilience outcomes.

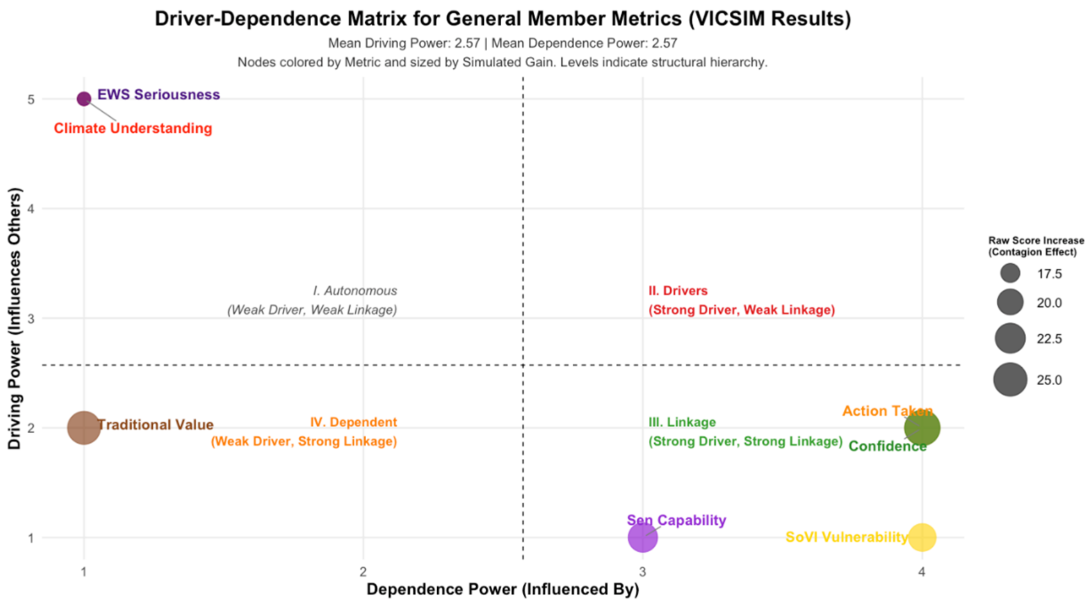


Figure 8. Driver-Dependence (MICMAC) Matrix.

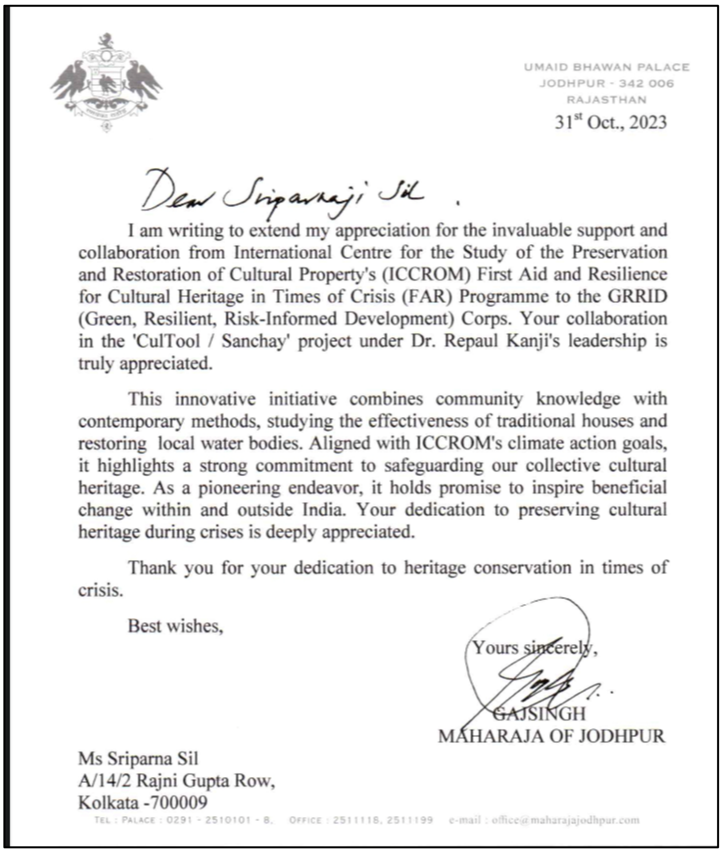
5. Discussion and Conclusion

5.1. The Paradox of Contagion: Behavior over Cognition

The Agent-Based Simulation results highlight a fundamental paradox in social diffusion within the Jodhpur context. While abstract climate science understanding is essential, it is the slowest variable to propagate, demonstrating a 1.6× greater difficulty in transmission compared to the psychological state of "Action Confidence" and the resultant "Action Taken". This finding aligns strongly with the literature on behavioural contagion and social norms, particularly the concept of Social Learning Theory [21], which posits that learning often occurs through observation and imitation rather than direct instruction. The women-led Hathai acts less as a lecture hall for climate science and more as a trusted source for observing successful coping behaviours. When a peer agent demonstrates high Action Confidence and visibly implements a climate-smart traditional practice, this performance is adopted quickly as a new social norm. This bypasses the need for the General Member to first master the complex scientific principles of climate change, confirming that in high-trust, tight-knit communities, trust is a faster diffusion medium than pure data. This has significant implications for climate communication, suggesting that interventions must prioritize showcasing visible, peer-endorsed action rather than focusing exclusively on cognitive knowledge transfer.

5.2. The Structural Necessity of Traditional Ecological Wisdom

The Interpretive Structural Modelling analysis (Figure 7) critically positions Traditional Resilience as a Linkage Variable at Level 2, mediating between foundational knowledge (Level 1) and ultimate outcomes (Level 3). This structural placement validates the central hypothesis of the research. Traditional ecological wisdom is not merely an antiquated relic, but a crucial functional mechanism in the resilience pathway. In the absence of a strong Traditional Resilience component, the influence of abstract Climate Understanding would likely dissipate without translating into tangible action. This acts as a cultural bridge, converting an external, abstract threat (climate change) into an internal, actionable framework (Hathai-endorsed traditional practices). This concept supports the Cultural Theory of Risk [8], which argues that risk is perceived and acted upon in ways that reinforce existing cultural narratives, thereby flipping the narrative from being un-operational due to gender-based hierarchies to celebrated hyperlocal climate action with realised benefits. This stands proven when the Maharaja (King) of Jodhpur appreciated the scientific demeanour in championing place-based wisdom and culture for hyperlocal climate action. The letter of appreciation is presented as Figure 9.



UMAID BHAWAN PALACE
JODHPUR - 342 006
RAJASTHAN

31st Oct., 2023

Dear Sriparnaji Sil.

I am writing to extend my appreciation for the invaluable support and collaboration from International Centre for the Study of the Preservation and Restoration of Cultural Property's (ICCROM) First Aid and Resilience for Cultural Heritage in Times of Crisis (FAR) Programme to the GRRID (Green, Resilient, Risk-Informed Development) Corps. Your collaboration in the 'CulTool / Sanchay' project under Dr. Repaul Kanji's leadership is truly appreciated.

This innovative initiative combines community knowledge with contemporary methods, studying the effectiveness of traditional houses and restoring local water bodies. Aligned with ICCROM's climate action goals, it highlights a strong commitment to safeguarding our collective cultural heritage. As a pioneering endeavor, it holds promise to inspire beneficial change within and outside India. Your dedication to preserving cultural heritage during crises is deeply appreciated.

Thank you for your dedication to heritage conservation in times of crisis.

Best wishes,

Yours sincerely,

GAJSINGH
MAHARAJA OF JODHPUR

Ms Sriparna Sil
A/14/2 Rajni Gupta Row,
Kolkata -700009

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Figure 9. Letter from Gajsingh II (Maharaja of Jodhpur) appreciating and acknowledging the role of culture in climate action.

By scientifically validating traditional practices (e.g., the thermal efficacy of vernacular architecture), the intervention makes climate action culturally legible and socially acceptable, thereby minimizing the social friction that typically impedes change. The linkage function proves that localized resilience efforts must be rooted in culturally specific, pre-existing behavioural scripts to achieve systemic efficacy.

5.3. Decentralized Governance and the Enhancement of Sen's Capability

The ultimate success of the women-led *Hathai* model, as evidenced by the high dependence power of Social Vulnerability Reduction *and* Sen's Capability at the top of the hierarchy (Level 3), points to the structural superiority of decentralized climate governance in urban arid or semi-arid zones. The enhancement of Sen's Capability is a direct measure of empowerment, indicating that the women leaders, through such community nodes, can gain the freedom to function—specifically, the agency to convert their latent traditional knowledge into recognized climate action. This moves beyond simple protection to genuine development. Furthermore, the Agent-Based Simulation's clustered network, which models a decentralized system, generated a robust spread, indicating the principle that in highly segregated or culturally distinct urban pockets, local knowledge hubs are more effective than monolithic top-down policy structures. This decentralized approach leverages the strong social capital within the Hathai groups, creating a more agile *and* contextual risk management system that is intrinsically more resilient against the systemic failures associated with centralized planning, aligning with contemporary literature on effective community-based disaster risk reduction.

5.4. External Moderators and Competitive Mechanics

While the result of the study highlights the internal efficiency of women-led Hathai nodes, it is essential to acknowledge that these decentralized units do not operate in a socio-technical vacuum. The real-world efficacy of the behavioural paradox is subject to external moderators that can either amplify or attenuate the transition from social contagion to physical risk reduction.

The simulation's interaction rate (α) serves as a composite proxy for social friction, but in practice, this friction is comprised of specific socio-structural moderators. Even when "Action Intent" propagates successfully through a Hathai node, the final conversion into physical risk reduction" may be blocked by infrastructure gaps. For instance, a community member may possess the high intent to adopt vernacular water management practices, but restricted access to reliable water infrastructure or financial capital acts as a bottleneck. In such cases, the social engine of the Hathai is attenuated by the material realities of the urban environment. Conversely, the Hathai effect is amplified by the high "Traditional Practice" baseline identified in this study. Because climate actions are framed within the trusted language of intergenerational wisdom, the social cost of adoption is lowered, allowing the contagion to bypass the cognitive resistance often found in top-down, purely scientific messaging.

The trust-based narrative of the Hathai must also compete with external information ecosystems that may offer conflicting signals. Official government messaging often relies on didactic, technical terminology regarding Heat Action Plans or Early Warning Systems (EWS). If this formal messaging fails to align with the place-based advice of the Hathai leaders, it may create a social dissonance that slows the adoption rate. Rapid urbanization in Jodhpur introduces commercial influences that may prioritize non-resilient modern comforts over traditional sustainable practices. The Hathai node acts as a defensive social mechanism against these influences, though its success is contingent upon the frequency and depth of the deliberation (as explored in our sensitivity analysis).

By systematically analyzing these moderators, this study moves toward a more balanced structural narrative. We recognize that the patterns attributed to the Hathai could be replicated or dampened by external interventions. However, the model suggests that even in a high-friction environment (α), the Hathai provides a resilient social infrastructure that formal climate governance can—and should—leverage to ensure that policy intent actually translates into community agency.

6. Conclusions and Policy Implications

This study offers a plausible structural narrative for understanding the mechanics of women-led climate action in the culturally complex urban environment of Jodhpur. By pairing Agent-Based Simulation (ABS) with Interpretive Structural Modelling (ISM), the research provides two key insights into hyperlocal climate governance: first, the simulation suggests that the diffusion of confidence and behavior outpaces the diffusion of cognitive knowledge; and second, the model illustrates how traditional ecological wisdom (Traditional Practice) acts as a critical linkage mechanism that converts abstract awareness into reduced social vulnerability.

While the simulation utilizes a stylized synthetic population intended for scenario exploration rather than precise real-world prediction, the convergence of psychometric data and computational modeling offers a novel framework for integrating computational social science with theoretical resilience indices, advancing existing studies [22]. The application of ABS to model the Hathai phenomenon, reframed here as a process of leader-weighted peer deliberation, combined with the causal hierarchy provided by ISM, demonstrates a promising mixed-method approach for investigating decentralized governance. This methodology is particularly relevant for studying non-Western, high-context societies where traditional social networks hold significant structural potential.

Rather than definitive proof, the findings generate a set of hypotheses that suggest a fundamental re-evaluation of climate action strategies in semi-arid regions:

- Shift from Knowledge Transfer to Behavioural Reinforcement: The model indicates a conditional advantage in pivoting policy away from purely didactic educational programs. Instead, resources could be directed toward facilitating peer-to-peer co-learning spaces (e.g., Hathai nodes) where women leaders model and validate actionable behaviours through high-trust social ties.
- Institutionalization of Traditional Resilience: Official policy documents, such as Heat Action Plans, could benefit from formally recognizing and integrating traditional ecological knowledge (e.g., specific dietary practices, clothing choices, and vernacular water management). The study suggests that moving this knowledge from the domestic sphere into the public policy domain could structurally reinforce the "Traditional Resilience" linkage variable.
- Invest in Decentralized Nodes: The simulation illustrates the potential efficacy of decentralized, hyper-local, women-led groups. Government and non-governmental organizations might view these nodes as effective delivery mechanisms for enhancing community agency (Sen's Capability) and facilitating social vulnerability reduction, even in environments with high social friction.

Future Work: Expanding the Scope of Agency

A recognized limitation of the current model is the stylized, unidirectional influence flow from the trained Participant Agent to the General Member Agent. While this provides a conservative estimate of intervention impact, it does not account for the lateral, peer-to-peer influence characteristic of true Hathai gatherings. Furthermore, factors such as entrenched gender norms and resource access were treated as components of a composite social friction coefficient (α) rather than individual variables.

Future research should refine the ABS network topology to include bidirectional, weighted links between General Members and explicitly model external moderators such as socio-economic constraints. This enhanced model would allow for the simulation of homophily, group-level emergent norms, and potential behavioral decay, providing a more complex and nuanced representation of community-level dynamics in decentralized climate governance. This would move the framework from a structural narrative toward a more robustly calibrated predictive tool.

Author Contributions

R.K.: conceived the idea and developed it; S.S.: assisted in conducting the workshop and survey. J.M.: assisted in drafting the manuscript. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The workshop and survey conducted for this study was organised through the Sambhali Trust in Jodhpur through their local network. The participation of women in the workshop was facilitated by the Sambhali Trust within the Memorandum of Understanding signed between the Sambhali Trust and GRRID Corps.

Informed Consent Statement

The workshop and survey conducted for this study was organised through the Sambhali Trust in Jodhpur through their local network. The Sambhali Trust ensured that the participants provided there informed consents before engaging themselves in the workshop and survey.

Data Availability Statement

The data used in this study is held with the Sambhali Trust and can be made available on justified request.

Conflicts of Interest

In addition to that, the authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Use of AI and AI-Assisted Technologies

AI or AI-assisted technologies were not used in this work.

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