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REVIEW

The Effects of Sudden Storm Events on Outdoor Sporting and Leisure Activities: Risk Assessment and Adaptation Strategies

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ABSTRACT

The acute and complex risks of outdoor sporting and leisure activities are caused by the rapid development of hazardous conditions, in most situations, little lead time for warning, and compound effects (e.g., lightning, extreme wind, hail, heavy rain, flash flooding, and water-based squalls). The interdisciplinary evidence in this review is synthesized by a storm-to-impact chain model of relating meteorological hazards to outcomes via intermediate processes of information, decision authority, and protective action and compliance. We come up with a typology of storm scenarios and exposure situations between fixed venues, linear path events, and distributed recreation and define critical determinants of vulnerability and adaptive capacity, such as the microgeography, shelter performance, and flow capacity, the maturity of governance, redundancy of communication, behavioral response, and equity-related constraints. The strategies of adaptation are overlaid onto the mechanisms that enhance the connections between the links in the chain, and it is important to note that corresponding individual interventions (e.g., improved nowcasting) cannot be done when other links are weak. Coherent portfolios will result in effective risk reduction through situational awareness, time-to-shelter hazard-aware triggers, and the combination of hazard-compatible shelter and movement planning with situational-aware and inclusive action-based messaging and institutionalized learning through after-action review and near-miss reporting. We suggest principles of implementation and metrics of evaluation that emphasize the performance of processes (time-to-decision, time-to-shelter, message reach and comprehension, and movement bottlenecks) as opposed to infrequent endpoint results. Missing links such as comparative efficiency of interventions, standardized reporting on disruptions and near-misses, and equity-oriented

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research on access to warnings, shelter viability, and adherence will remain unresolved.
Keywords: Sudden Storms; Outdoor Recreation; Sport Safety; Risk Assessment; Adaptation Strategies

1. Introduction

The leisure and sporting activities in the outdoors are more and more influenced by variability in weather, yet there are few risks that can be as pressing to safety and continuation as sudden storms [1]. Comparto seasonal or gradually changing factors (such as an extended rainfall or heat), sudden storms may escalate in intensity between benign and dangerous in minutes, lessening the time span of detection, decision-making, and protective measures. Such a limited decision window is coupled with the fact that the environment where this occurs is usually high exposure in nature, open fields, elevated terrain, water surfaces, low-density sheltered trail systems, and temporary event facilities. Consequently, risk does not just depend on the intensity of meteorological conditions, but also on early warning arrival, concentration of exposure, and mobility restrictions, as well as the ability of organizations and individuals to act on the information as soon as possible [2,3].

The extent of outdoor participation in sudden storm risk is across the board. Formal, structured sport and mass sport, such as school sports, community sports, tourism, marathons, cycling races, triathlons, and recreational events in outdoor festivals, are managed with distributed roles between the organization, venues, coaches, referees, volunteers, and local government. Simultaneously, informal recreation and nature-based recreation, such as hiking, climbing, camping, fishing, paddling, surfing, boating, and sightseeing, are often individual judgement based, with participants scattered over complicated terrain and at times miles away from engineered shelter. In both situations, lightning injury, wind-related trauma, slipping falls, drowning caused by quick run-off or squalls over water, and hypothermia in cold rain when individuals are wet, fatigued, or immobilized can be direct injuries. The indirect implications are equally huge: evacuations and cancellations, economic losses and insurance costs, reputational effects on organizers and destinations, psychological stress and decreased trust, and long-term alterations in risk perception that have the potential to alter participation patterns [4–6].

Although there has been extensive exposure, research, and practice, advice is still interdisciplinary, and it does not always fully integrate. Meteorological science can offer more and more advanced severe weather detection and short-range prediction; however, operational decisions regarding the suspension of play, rerouting courses, or evacuating crowds rely as much on local factors and human behavior as on the likelihood of hazards. Emergency management and safety science provide models of incident command, preparedness, and mass movement, but outdoor sport and recreation circumstances present unique situations-competitive motivation, spectators, temporary structures, scattered paths, and liability-sensitive governance that make it hard to directly apply generic emergency procedures. Research in risk communication highlights discrepancies between messages and compliance, especially when there is a lot of uncertainty or frequent alerts lead to false-alarm fatigue, but as a rule, it lacks connection with the physical reality of shelter capacity, bottlenecks in egress, and unequal information accessibility. Due to these reasons, sudden storm safety should be viewed as a coupled socio-technical system where the dynamics of hazards are applied to exposure patterns, vulnerability, decision authority, infrastructure, and behavioral response [7,8].

Outdoor participation is a unique category of risk due to the combination of a rapid appearance, multiple hazards, and high dependence on the conditions [9]. The fast onset restricts the time in which to evacuate individuals out of the exposed zones to secure locations, particularly when the individuals have been distributed over linear tracks, when the spectators are tightly congested, or when there are movement constraints on kids, the elderly, and people with disabilities. Multi-hazard potential implies that the pre-eminent threat may change rapidly: a lightning problem may turn into a wind and debris problem, and then a flash-flood problem as the heavy rain is concentrated in drainage ways. Context dependence means that the same storm can have extremely varied results depending on the availability and quality of shelter, terrain, path geometry, crowd density, staffing, and the clarity and enforceability of action protection criteria. A thunderstorm could be controlled in a well-equipped location with substantial shelters and with established protocols, but could be disastrous on a bare ridge, a bare playing field, a busy coastline, or a river valley subject to flash flooding. Such differences underscore the value of the element of storm intensity on its own as a poor predictor of sport and recreation contexts.

The leisure and outdoor sports field is another area that has some motivational and cultural aspects that influence risk. Competitive situations may promote persistence in marginal conditions and postpone kinds of protection choices, especially when the weather is perceived to be intermittent, localized and ambiguous. When viewers observe that other individuals are still there or warning signs are not appropriate in weather conditions, they may underestimate the danger. In informal recreation, hazards are overcome by people underestimating the time to shelter, by overestimating the rate at which the situation may alter, or by depending partly on the information streams. The increased rates of participation in endurance and adventure recreation activities have also led to the influx of new participants into the setting where severe weather awareness and reaction are not instinctive. All of these human factors are not substitutes for the physical hazard; they determine whether the precautionary measures are taken in time to be of any effect [9,10].

In this review, a practical definition of sudden storm events is embraced as rapidly changing storms that have the potential to create hazardous situations with short lead time. The hazards to be taken into account are lightning and thunderstorms; strong winds, related to gust fronts, downbursts, or squalls; hail and debris shot by the wind; heavy precipitation with localized flash flood risks, or rapid runoff; sudden cold rain and temperature drops, posing a risk of hypothermia; and severe convective events, where they occur regionally, having low-probability, and high-consequence hazards. Outdoor sporting activities are regarded as systematic and structured engagement in sport or bodily rivalry that occurs in outdoor settings, such as training sessions, matches, competitions, and endurance events. Outdoor leisure includes informal or semi-structured recreation, which includes hiking, camping, climbing, paddling, boating, fishing, beachgoing, and nature-based tourism. These classes are deliberately intersected. Most recreation activities are held in types of settings that are similar to recreational ones (such as trail running or open-water races). Instead of polarities of sport and leisure, this review focuses on a spectrum of governance and responsibility between a highly centralized governance of events and individual decision-making and the question of how this spectrum influences risk and viable measures of adaptation [11,12].

Risk assessment has been widely applied to encompass qualitative and quantitative methods of risk assessment that describe the likelihood of hazard, exposure, vulnerability and consequences of the hazard and decision levels to initiate protective measures [13]. The adaptation strategies refer to actions that will mitigate destruction or disturbance prior to, throughout, and following the unexpected storm incidents [14]. They might be technical, e.g., integration of alerts and decision-support systems, infrastructural, e.g., placing shelters, enhancing drainage and wind-safe temporary constructions, organizational, e.g., stop regulations, authority models, drills, and integration of incident command, communicative, e.g., clear action-oriented messages and multilingual templates, behavioral, e.g., education and compliance interventions, and policy-based, e.g., standards, duty-of-care advice, incident and near-miss reporting requirements.

The reason why an integrative synthesis is timely is that outdoor participation is growing in most areas as the operational environments are becoming more complex [15]. There are bigger events, bolder routes and temporary infrastructure that see more people exposed, and it becomes logistically more challenging to get them all away in time. Simultaneously, the information environment has become varied. There can be several, even conflicting messages to the participants in terms of official alerts, event apps, venue screens, social media, and peer networks, and it is unclear what to do, and who to listen to. In reality, effectiveness depends on whether the warnings are translated into understandable, reliable, and practical guidelines that reflect the actual limitations on shelter and exit. Even proper warnings may not help prevent harm, even when the evacuation routes are congested, the evacuation routes prove to be too far, or when the authorities are disjointed.

Research on what works in such situations is still unequal. Local precedent, institutional liability issues, or general guidelines, instead of comparative effectiveness research, often influence many of the operational policies. There are settings with elaborate lightning procedures but less planning on how to deal with flash flooding along the routes, and settings with emphasis on evacuation, but fail to consider the communication design and compliance measures needed to enable high-speed movement. Informal recreation advice can be used to propagate broad awareness, but not to deal with decision-making in the context of low forecast confidence or exposed terrain reality. Considerations of equity and accessibility are also not well-developed most of the time. Response to sudden storms is based on mobility, access to language, knowledge of local hazards, access to instantaneous information, and access to safe shelter. Adaptation efforts fail to explicitly consider these factors and, in some cases, therefore, end up shielding the already well-resourced and leaving others in a disproportionately vulnerable position [16,17].

Based on that, this paper summarizes the existing information about the impact of sudden storm occurrences on outdoor sports and leisure and coordinates the literature into a framework of mechanisms that contribute to risk evaluation and functional adaptation. The review is informed by three questions: what are the most common hazards associated with storms that impact the outdoor environment, through what mechanisms do the hazards lead to harm and disruption; how the context of exposure, vulnerability, and capacity (infrastructure, governance, information flow, and human behavior) influence their effects and what evidence is there of effectiveness and operational trade-offs; and what adaptation strategies can be implemented in various settings [18–20]. Instead of presenting sudden storm safety as the forecasting problem per se, this review considers it to be a decision-and-action chain where strength in one part cancels the strength in another place.

This synthesis provided here is aimed at researchers as well as practitioners, e.g., the organizers of events, operators of the venues, coaches, outdoor educators, land managers, and safety regulators. It incorporates meteorological hazard factors with operational preparedness, infrastructure facts, and behavioral response, indicating the areas of intervention to coincide with particular failure modes. The general assumption is that sudden storm risk can be minimized by enhancing the entire process of hazard recognition to protective response, whether through enhancing hazard detection and situational awareness, improving authority and setpoints, making shelters and evacuation routes realistic and accessible, communicating effectively and responding to learning, and systematically learning through incidents and near-misses [21]. The subsequent sections build up this integrative framework, introduce a typology of storm situations and exposure situations, systematize determinants of vulnerability and adaptive capacity, and map the adaptation strategies on mechanisms and priorities to be evaluated when implementing the adaptation strategies.

2. Conceptual Framework: The Storm-to-Impact Chain

Outdoor sport and leisure environments. Sudden storm hazard is best thought of as a time-compressed system where the hazard is transformed into harm by a series of information, decisions, and actions. The review takes a storm-to-impact chain structure that connects atmospheric conditions to operational outcomes through a series of performing steps that can increase or decrease the risk. The framework is keen to point out that meteorology is rarely the cause of injuries, fatalities, and mass-disruptions, but rather they are developed when the warning signs that trigger hazards are rapidly changing, and when exposure is of high intensity coupled with low protective capacity, and delays or failures in converting warnings into protective action. The chain conceptualization of risk is helpful in contexts of heterogeneous risk where some types of risk management are considered, e.g., managed venues, remote recreation, etc., as it illustrates where interventions can be laid and how weaknesses in one chain can be counterbalanced by strengths in others [22,23].

2.1. From Hazard to Consequences: A Systems Perspective

On the upstream end of the chain is the meteorological hazard, which comprises lightning, severe wind, hail, heavy precipitation, and the rapid warming and cooling of air, which may be experienced as convective storms [24]. These risks are not predictable and may change rapidly over a short period of time. The end of the chain also has downward consequences that are significant to both the publicly available health and sport/leisure systems, including acute injuries and casualties, emergency medical use, evacuations, delayed events and cancellations, damaged infrastructure, and long-term psychosocial and economic impacts. The fundamental premise is that results are yielded through the interaction of the hazard and three modulating factors, which include exposure, vulnerability and adaptive capacity. The exposure deals with harm in the path, and duration of exposure; the vulnerability deals with susceptibility, considering the physical and social conditions, and the adaptive capacity deals with the capability to identify (risk), make decisions to protect against it, and take those decisions so they are implemented within the available time.

This framing is consistent with existing ideas of risk, but puts more focus on operational facts that are unique to outdoor sport and leisure [9,25]. Most of the activities require movement of participants, asymmetrical distribution of shelters, as well as powerful motivational forces that are capable of delaying self-protective behavior. Decisions made in organizations should also go through structures of governance that are not always clear during times of panic. In informal recreation, the responsibility is personalized, and the capacity to protect is limited due to the terrain, distance, and substandard information. The storm-to-impact chain thus does not consider risk but a moving process that occurs with respect to time, communication, power, and movement. Sudden storm risk is generated in a storm-to-impact chain, of which hazard detection is coupled with information translation, decision authority, protective action, compliance, and outcomes, as summarized in **Figure 1**.

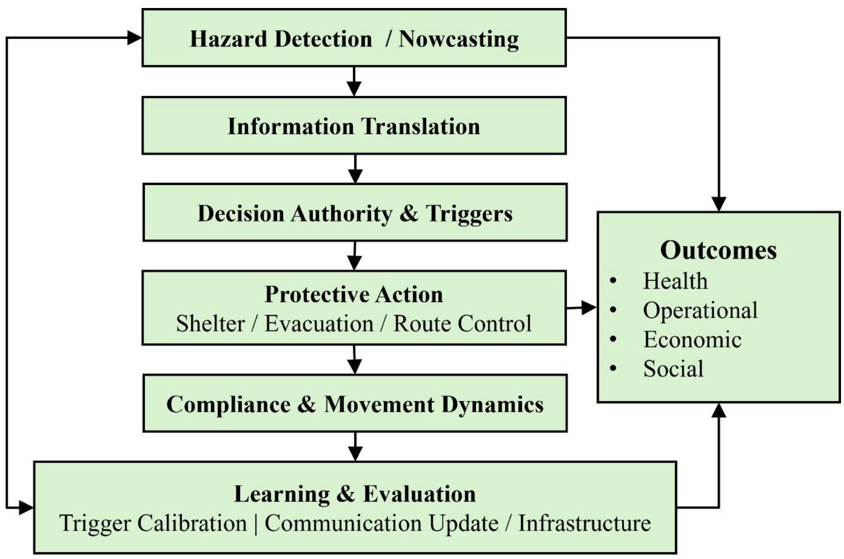

Figure 1. Storm-to-impact chain for sudden storm risk in outdoor sports and leisure.

2.2. Warning and Information: Detection, Translation, and Credibility under Time Pressure

The initial significant transformation within the chain is when the meteorological signals are picked and converted into information available to the decision-makers and participants [26]. Detection can be based on forecasts, radar-based nowcasting, lightning detector networks, localized observation, or official weather notifications. The applicability of these signals within operations is, however, determined by their ability to give lead time that is actionable in the individual setting. The lead time is not only a technical feature, but it is the time during which an organization or a person may take protective measures and perform them (shelter or evacuation). Storm warnings that come after a location is already overwhelmed, or people have already been bound to open lengths of a route, are of little or no value as protective, even when they are meteorologically precise.

Translation refers to meteorological information that is converted into context-dependent implications [27]. Practically, this step can be easily broken down due to the fact that weather products do not easily convey operational feasibility but rather hazard potential. This is because a statement that there will be lightning in a radius or that there will be terrible winds does not state whether a race should be stopped, whether a coastline should be cleared, or whether an exposed mountaintop way should be forsaken. Translation needs to be localized which means shelter quality, time to shelter, terrain limitations, and the nature of the exposed population. In the case of weak translation, organizations will become inconsistent, and individuals may think about risk using their own heuristics that underprice low-frequency, high-consequence outcomes.

Truthfulness and trust are what define action or not. There is competition between warnings and visual cues, peer behavior, as well as the cost of interruption in both formal and informal settings. False-alarm fatigue is a phenomenon that occurs in cases where repeated warnings that do not correlate with perceived danger are involved, making one less responsive when an actual threat occurs[28,29]. On the other hand, too conservative triggers may destroy the confidence of participants and stakeholders and cause pressure to postpone decisions. The storm-to-impact chain considers credibility as a functional parameter that is influenced by lack of clarity of messages, consistency, source authority and perceived congruity between warnings and conditions experienced. Effective communication is the one that does not remove uncertainty, it only renders it visible and evokes the proper protection behavior.

2.3. Decision-Making and Authority: Thresholds, Incentives, and Accountability

The other connection after information is decision-making. In outdoor sport and recreation, decisions are usually shared amongst a variety of actors whose priorities might not coincide with one another. In structured sport, the power can be distributed among event directors, officials, coaches, venue managers, medical teams and local agencies. Schools and communities may have institutional policy limits to decision authority and may have a sense of duty-of-care. During mass participation events, the dispersive nature of the space occupied by the participants and the reputational and financial cost of cancellations can make decisions complex. In informal recreation, the decision-making process is personalized, but highly affected by group processes, sunk costs, and social accounts of toughness or success[8,30].

The speed and consistency of decisions in decision-making focus on thresholds and triggers[31]. A threshold is a criterion that correlates observed or projected conditions with prophylaxis, such as the suspension of activity, evacuation, rerouting, or the cancellation of an event. The quality of a threshold is based on the fact that it should be made to suit the local environment and the time required to act. As an example, a stop decision should be made in time so that the participants can seek shelter before it is too late. In case of vague, contested, or unknown thresholds, the process of making a decision is likely to be postponed, negotiated, or reversed, which takes up valuable time. Delays have consequences, especially when it comes to hazards such as lightning and sudden wind, where extreme conditions can come with very little visual warning.

Rewards and responsibility influence the application of thresholds as desired[32,33]. The presence of competitive and commercial pressures may also cause decisions to be biased toward continuation, especially in situations where parallel conditions are unclear and disruption costs are salient. The problem of liability may be used to make biased decisions to interfere with the decisions without proper planning of the effects of transporting large crowds during storms. The storm-to-impact chain emphasizes that not being safer, more conservative, may be the action that results in poorly controlled movement into new hazards, e.g., evacuation into wind-exposed zones or directing people to be evacuated into flood-prone underpasses. Decision latency and consistency can be improved by having accountable structures that make clear to the decision maker, on what basis and how decisions are delivered, but these need to be accompanied by realistic action plans.

2.4. Protective Action and Movement: Shelter, Evacuation Dynamics, and Compliance

The consequences of such a decision are based on the implementation of protective measures. The most limited step in the chain is usually execution since it is framed by physical infrastructure, mobility, and human behavior. In a fixed venue, protective action is generally performed by taking the participants and spectators to safety, putting out stops, and securing equipment and emergency access. In route-based events, the necessary protective measure can be the termination of runners or cyclists along a scattered route, determining the closest safety points, improving transport, or hiding in place. Some of the protective measures in remote leisure environments include reversing route, leaving exposed land, leaving water or seeking natural or artificial protection[34,35].

Shelter is core, though dissimilar in quality. Shelter covers lightning and extreme wind and is available within the time parameter. Most outdoor environments do not have enough shelter space to accommodate maximum occupancy, and most of the so-called shelters have partial protection against certain risks. A building that keeps the rain out might not be lightning-safe; a tree canopy might be psychologically safe but physically unsafe with falling branches or ground electricity; a poor shelter might be safe in the wind, but unsafe in a flash flood. The chain structure thus does not consider shelter to be a binary entity but to be a multi-dimensional feature, that is, it is close, has the capacity, protects against hazards that are of interest, is accessible to a variety of users, and is able to control entry and movement without bottlenecks [36,37].

Movement and evacuation bring dynamic risks, which can be as big as the risk itself. Movement of crowds may result in congestion, falls, trampling, and delay, exposing human beings to a longer time. The evacuation routes may be through wide concourses, small bridges, steep tracks, or lakeside tracks, which are dangerous during high winds or heavy rainfall. The movement decisions should also take into account the chances of changing the hazard profile, like lightning risk to flash flooding, as the rainfall increases. In dispersed recreation, movement is limited by topography, exhaustion, and expertise, and the most prudent course of action is not to run away, but often to seek safety in place. These complications highlight the need for protective action planning to be hazard-specific and context-specific, and not on generic advice [38,39].

The performance of any protective measure is mediated by compliance. In formal contexts, obedience is determined by the intelligibility of the instructions, the assumed legitimacy of power, and the degree to which the protective behavior is drilled and adopted as a normal practice by society. In the informal context, risk perception, group leadership, and the presence of safe alternatives are the factors of compliance. Strategies of communication that identify literal action, give reasons in brief, and give congruency across media can enhance compliance but not address structural gaps like lack of shelter or unrealistic assumptions of time to shelter. In the storm-to-impact chain, compliance is considered to be an emergent feature of the message design, social circumstances, and environmental practicability.

2.5. Outcomes, Feedback, and Learning: Closing the Loop

The last connection in the chain is the group of consequences of hazard, choices, and acts interaction. Short-term effects are injuries, deaths, close calls, and emergency operations. Operational outcomes as delays, cancellations, route changes, and evacuation and sheltering operations, are operational. Direct disruption costs, loss of revenues, destruction of both temporary and permanent infrastructure, and insurance effects are types of economic outcomes. The psychosocial outcomes are responses to stress, perceived safety changes, perceived trust in the organizers or authorities, and follow-up avoidance or substitution behavior. Notably, these effects are unevenly spread. Differential vulnerability refers to the fact that children, the elderly, visitors, who are not aware of local hazards, and people with mobility or sensory impairments can be at greater risk during the exposure and evacuation, especially in areas where no available shelter and comprehensive communication exist [16].

The processes of learning predetermine the chain strengthening with time. However, teaching in this field is usually constrained by inconsistent reporting, non-standard near-miss reporting, and the propensity to view cancellations as operationally defined events instead of data-carrying safety incidents [40]. Having incident debriefs and after-action reviews can help identify bottlenecks in authority, communication, and movement, but it requires an ability to create actionable changes regarding thresholds, infrastructure, staffing, and training. The storm-to-impact chain views learning as a feedback loop, which renews upstream connections: how warnings are tracked, how thresholds are established, how authority is delegated, and how safeguarding measures are performed. In the event of systematic feedback, the chain progresses to adaptive resilience compared to a reactive response.

2.6. Implications of the Framework for Synthesis and Adaptation

Implementation of the storm-to-impact chain has two implications on the interpretation of the evidence base. To begin with, the quality of any given adaptation approach depends on the quality of nearby connections. For example, better nowcasting will not protect against damage where it is unclear who has power or where shelters are not available; equally, excellent shelter infrastructure might fail to do the job when warnings are not heeded or decisions postponed. Second, the measures of evaluation should be based on the performance of the chains, but not on endpoint results alone.

In order to emphasize the interactions of these links in settings, **Figure 2** incorporates the hazards, exposure contexts, vulnerability drivers, and adaptive capacity into a coupled system of storm-related outcomes interpretation. Third, the chain is not merely linear; feedback loops operate across links in both reinforcing and balancing directions. For example, repeated false alarms or ambiguous warnings may erode trust over time, weakening the warning-to-decision and decision-to-action links—a balancing loop that reduces system responsiveness. Conversely, well-managed near-misses with transparent after-action reviews can strengthen decision thresholds, improve message credibility, and accelerate future protective actions, creating a reinforcing loop that builds adaptive capacity. Recognizing these loops is essential for designing learning-oriented safety systems that avoid the trap of reactive, event-driven improvements. The coupling of reinforcing and balancing feedback is illustrated conceptually in **Figure 2**, where hazard, exposure, vulnerability, and capacity pathways interact dynamically rather than statically.

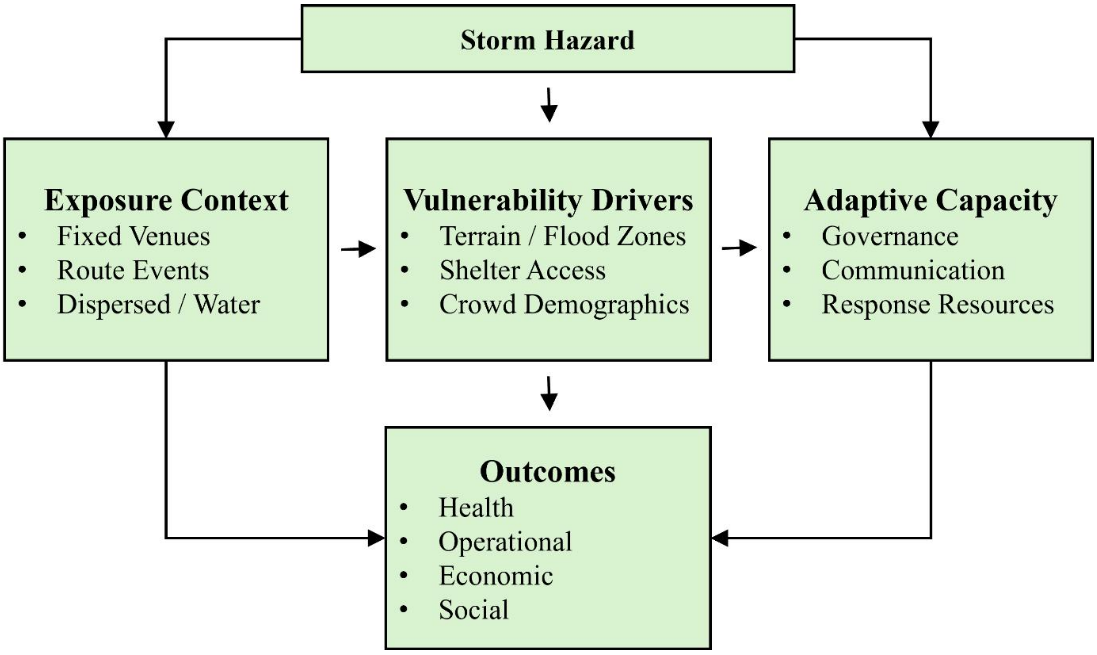

Figure 2. Coupled framework integrating Hazard–Exposure–Vulnerability–Capacity pathways.

The time-to-decision, time-to-shelter, message reach and understanding, and observed movement bottlenecks are the measures that can offer an actionable insight even in the case of the uncommon severe outcomes [41]. These process measures can be used to make comparisons across settings that have inadequate counts of direct injury (or that are too inconsistently documented) and so cannot be used to draw significant inferences.

In the remainder of this review, this framework is used to organize the literature on storm scenarios and exposure contexts, determinants of vulnerability and capacity, and adaptation strategies. The aim is to connect what is known about hazards to the real operational and behavioral processes through which risk is produced and can be reduced.

3. Typology of Storm Scenarios and Exposure Contexts

The effects of sudden storms on outdoor sport and leisure are heterogeneous as storms vary in terms of predominant mechanism, spatial footprint, duration, and predictability, whereas outdoor activities vary in terms of exposure geometry, mobility, and shelter capability [42]. Synthesis Typology will be helpful in the sense that it simplifies the complexity of storm events into the categories of scenarios on the basis of which they have similar operational implications. The definition of the scenario classes will be determined in the context of this review, not only on the meteorological characteristics but also by the rate at which they pose a threat to exposed persons and what mitigating measures are practically possible. Coupled with hazard typology, exposure contexts define whether safety lies centrally to centralized decisions (managed venues), distributed control (route-based events), or individual judgement (dispersed recreation). This section thus defines recurrent storm situations and then outlines the major exposure situations where outside sporting and recreational activities take place.

3.1. Lightning-Dominant Convective Scenarios

Storms that are dominated by lightning are some of the most impactful situations in outdoor sports, as they may pose a fatal threat even in cases when the amount of rainfall is low and the winds are not very strong [43]. In its workings', lightning risk is difficult to manage since it seems to be intermittent and since the most noticeable indicators of danger might not follow the initial lightning strikes. In most outdoor locations, the intensity of the storm is not the critical factor; rather, it is the time that can be used to move the people and spectators out of the lightning-prone area. This renders lightning-dominant situations especially vulnerable to decision thresholds, communications latency, and shelter capacity. The spatial scale of concern is also greater than the immediate venue, as lightning may strike at significant distances around the rain core, and risk may exist when the storm is coming and going. As a result, lightning-dominant situations often put pressure on governance structures: they are often forced to make decisions before the conditions are perceived to be dire, and obedience is conditional upon the belief that the disruption is warranted.

Lightning-dominant situations in leisure and informal recreation are particularly dangerous in terrain with limited safe refuge, e.g., ridgelines, open water, alpine conditions, and plains areas with no trees [44]. In this case, the operational challenge is that the time-to-shelter can be greater than the time-to-hazard, and the selection option can be limited to less-than-perfect options. Decisions that expose one risk to another and vice versa, like trying to make fast progress up and down slippery ground or staying where shelter is not ideal, can therefore be forced by lightning risk.

3.2. Wind- and Debris-Dominant Scenarios

Wind-dominant situations involve quick spurts, down surges, squalls, or extreme straight-line winds, which may develop quickly and pose immediate trauma risk due to flying debris, temporary installation system failure, tree and branch dropping, and imbalance [45]. In the case of outdoor sport and event environments, wind is a hazard that does not usually allow a second opportunity since once it begins, it can be quite sudden and can focus its energy in locations of structural weakness like stages, scaffolding, tents, fencing, and signage. Protective action is also feasible even in the presence of a warning to operators to secure or de-energize structures in a short period, and the evacuation routes themselves are safe during high wind loads.

The wind-dominated situations are especially applicable to leisure environments (spectator-heavy and festival-surrounding) that involve temporary shelters and pressures that are represented by large crowds [46]. The direction under high winds can pose risks of falling in such cases, and opposing the evacuation, the safest course of action could be moving to sturdier buildings as long as they are available and adequately large. Wind-dominated situations are hazardous in backcountry recreation on exposures, cliffs, margins of the treelined areas and in water bodies, which can generate waves and loss of vessel control within a short period. The prevailing operational implication is that the wind hazards may quickly undermine the safety of the very measures that people may resort to escape, and it is of the essence to know about the hazard early and choose the route conservatively.

3.3. Hail and Cold-Rain Shock Scenarios

Hail falling and sudden cold-rain situations may also be injurious, both directly through the force of impact or indirectly by inducing panic motion, low visibility, and loss of manual dexterity [47]. Although the hail is usually regarded as a nuisance when compared to lightning, its practical value in sports and recreation is in its ability to harm large numbers of people within a small period, especially when their shelters are minimal, and the grounds are made wet. Cold-rain shock has the ability to hasten heat loss and raise the probability of hypothermia in individuals undertaking endurance activity, particularly in combination with wind and fatigue. Such situations are also in close interaction with the dressing options, access to dry shelter, and the capability of medical assistance.

Exposure to hail and cold-rain situations is salient where there is long-term exposure and a lack of shelter, i.e., open field sports tournaments, long-distance races, and outdoor recreation in high altitude or during shoulder seasons [47]. They can easily create complicated choices since the most observable risk can be precipitation, but the greatest downstream risk can be thermal stress following a storm, specifically when the participants are still wet and exposed or when any delays in evacuation prolong their exposure.

3.4. Intense Precipitation and Flash-Flood Scenarios

Flash-flood conditions are characterized by quick hydrological reaction to the heavy precipitation, which leads to rapid growth of water in the channels, underpasses, drainage paths, and steep slopes [48]. Such situations may be disastrous as they pose moving-water risks that are faster than the human ability to move and are hardly noticeable until they become imminent. In route-based missions, sports as well as recreational settings, the danger is enhanced since competitors might be channeled into bottoms, river crossings, canyons or urban drainage systems where water accumulates. Contrary to lightning that could permit hiding in strong structures, the risk of flash-floods may demand immediate evasion of particular landforms and planning of routes to be taken before the event.

As an operation, flash-flood scenarios require the localization of hazards. One part of a path can be hazardous and the rest of the route safe; a trail can be generally in use and a particular canyon deadly. This renders flash-flood risk very sensitive to spatial data, signs, as well as the capacity to close or divert certain routes promptly [49]. Flash-flood situations are particularly dangerous in informal recreation, where the visitor may be new to the area or may be misled by the apparent clarity of the sky overhead to think the area is safe. The reason is that the imbalance between the locations of rainfall and flooding is a widespread factor behind misjudgment and the lack of timely action.

3.5. Water-Based Squall and Rapid Wind-Shift Scenarios

In lakes, rivers, and coastal areas, sudden squalls and swift wind variations can change situations that can be controlled into dangerous situations in a few minutes [43,50]. The prevailing force can be the waves of wind power, capsizing, loss of propulsion control, or loss of connection with the shore, usually with a loss of visibility and heavy rain. In sport and leisure on water, the distance to the safe landing points, the skills of the participants, the type of the vessel, the use of flotation, and the presence of the safety craft and communication are considered the most important determinants of exposure. Since water conditions may quickly turn inexperienced sailors into a force of nature, precocious intuition is at the forefront, and preventive measures often must be undertaken prior to the arrival of the squall.

During organized water events, the ability to halt activity depends on the ability of organizers to communicate rapidly over a distributed field and the ability to extract the activity safely based on currents and wind. During informal recreation, use of personal judgment, on-site access to real-time warning systems, can lead to a delayed withdrawal, particularly when the persons are engaged in activity objectives or are geographically separated by storm visual indicators [51].

3.6. Severe Convective and Low-Probability, High-Consequence Scenarios

Low-probability, high-consequence hazards like tornadoes or severe convective winds are some of the contexts of sudden storms [52]. Although such consequences are infrequent compared to the usual thunderstorms, their possible hazard should be singled out in the environment with a high concentration of people. The operational issue is that such hazards require swift protective response in uncertainty and the protective response may vary compared to typical lightning or rain procedures. Specifically, the decision-making in terms of the movement should take into account the fact that evacuation may lead to more exposure, and shelter decisions should be resistant to the structural loads. In the case of sport and leisure systems, the implication is the most crucial that there must be an element of escalation logic in decision structures, in such a way that the rare but serious possibilities are included without the result of continual overreaction to ordinary storms**. Table 1**, which was used in this review, consolidates the storm-scenario typology, which links dominating hazard mechanisms to probable consequences and the protective-action implications these generate.

Table 1. Storm-scenario typology, dominant impact mechanisms, and protective-action implications.

Storm Scenario Class	Primary Hazard Mechanism	Typical Onset and Spatial Pattern	Likely Immediate Consequences in Sport/Leisure Settings	Protective Action Implications
Lightning-dominant convection	Cloud-to-ground lightning; ground current risk	Can precede heavy rain; risk extends beyond rain core	Fatal/serious injury potential; rapid disruption; lingering risk during approach/retreat	Decisions must be taken before visual severity; shelter must be lightning-safe and reachable within lead time
Wind/debris-dominant (gust fronts, downbursts)	High gusts; airborne debris; tree/structure failure	Abrupt onset; highly localized but severe	Trauma from debris; collapse of temporary structures; falls	Early securing of structures; avoid evacuating through exposed corridors during peak winds
Hail and cold-rain shock	Impact injuries; rapid cooling; reduced visibility	Short bursts; can occur with modest rainfall	Lacerations/contusions; panic movement; hypothermia risk in prolonged exposure	Immediate refuge from hail; thermal management planning for endurance participants after stoppage
Intense precipitation and flash flooding	Rapid runoff; channelized flow; inundation of low points	Spatially mismatched (rain upstream → flooding downstream)	Drowning risk; entrapment in canyons/underpasses; route severance	Terrain-aware closures/reroutes; move away from channels/low points; localized controls are critical
Water-based squalls/rapid wind shifts	Capsize risk; wave growth; loss of control	Minutes-scale onset; fast escalation on open water	Drowning/near-drowning; separation from shore; rescue access degraded	Early recall to shore; safety craft readiness; termination criteria must prioritize early exit
Low-probability, high-consequence severe convective events	Extreme winds; tornado risk in some regions	High uncertainty; rare but catastrophic	Mass casualty potential; major infrastructure damage	Escalation logic and refuge guidance must differ from routine thunderstorm procedures

3.7. Fixed-Venue Contexts: Bounded Exposure and Centralized Control

Facilities such as stadiums, fields, courts, and parks with designated zones of activities and controlled recreation facilities are considered fixed facilities and structures where participants and spectators are comparatively clustered [53,54]. Such settings are usually better equipped with governance systems and a communication framework, including public address systems, screens, staff, and signage. The main benefit is that all protective measures can be organized at the center, and shelter facilities can be preset and capacity-designed. Nonetheless, fixed locations may also establish bottlenecks of high-density exposure and movement. Where mass crowds are trying to move, time to shelter is also a factor of flow capacity and not simply a factor of distance. The context of the venue also determines the possibility of hazard-specific shelter, e.g., an area might be covered and safe in terms of rain, but lack enclosed areas where lightning cannot get inside, or it can offer strong shelter, but people have to walk through open areas to access it.

Preparation and quality of execution are thus one of the risk management factors that would make any fixed venue lean towards risk management [55]. Vigilant meteorological observation and prompt determinations can be more guarding, whereas the tardy determination may bring about a traffic jam that prolongs the exposure and exposes the secondary injuries. Physical aspects of the venue, such as entrances, concourses, stairways, and pathways of access, become part of storm safety performance.

3.8. Linear-Route Contexts: Distributed Exposure and Partial Control

Linear-route situations are marathons, cycling races, triathlons, trail races, and big walk situations where the individuals are spread along routes of differing shelter and topography. The exposure in such situations is non-uniform in that the various segments are exposed to varying levels of hazards and varying protective alternatives. Governance is also incomplete: organizers can establish policies and communicate on a large scale, but cannot stop movement immediately across the whole route and participants can be miles away and out of staff or shelters. Time-to-shelf is frequently the restrictive parameter, and it continuously changes throughout the course [56].

Such contexts are especially context-type sensitive. Lightning and wind are both faster than an organization can manage a coordinated stoppage, and flash-flood risk is likely to be confined to certain portions and thus be subject to coordinated closures should they be detected in time. Linear routes also pose problems in communication, which involves the redundancy of mobile alerts, course marshals, and briefing participants. The route-based environment is such that pre-event design is an adaptation strategy by itself: how to choose the geometry of the course, how to reduce the exposure at the identified hazards, and how to have access to solid shelter or extraction alternatives [56,57].

3.9. Dispersed and Remote Recreation Contexts: Individualized Decisions and Constrained Options

Examples of dispersed recreation settings are backcountry hiking, climbing, camping, paddling trips, and informal use of the beach or coastal areas where participants are distributed over large regions and are not necessarily linked to centralized communication [58,59]. In such environments, terrain and distance have a heavy influence over exposure, and the number of available options to protect against it might be restricted or unclear. The process of decision-making is personal and dependent on group aspects, experience, and risk perception. Since formal shelter might not be available, protective action can frequently imply route choice, timing, and evading dangerous terrain before the development of storms. When the hazards come, the best can be a limited trade-off as opposed to an optimal intervention, particularly in lightning and wind conditions, where even relocating can cause exposure to be more probable.

Incident response is also difficult in remote contexts. The access and rescue operations may be delayed by medical workers, and the effects of non-lethal injuries can be increased by isolation and environmental pressure. It means that vulnerability does not only concern how likely one is to be hit by a hazard, but also how badly things are going to be in case of limited response capacity. In such situations, adaptation is thus very reliant on anticipatory planning, education, and situational awareness as opposed to real-time centralized control [60].

3.10. Spectator-Dense and Hybrid Event Contexts: Coupled Sport–Leisure Exposure

The hybrid form can occur in many real-life contexts: tourism could be part of a festival with a competitive sport element, as well as an outdoor concert with recreational elements, or a destination event with a race element [61]. Such contexts have the ability to increase risk since they cluster large, heterogeneous crowds that differ in their attention, movement, and knowledge of the local risks. Risk salience may be lowered by the presence of alcohol, music, and competing stimuli, and economic pressure may be heightened by the desire not to postpone or abandon activities. Communication should thus target its participants and spectators, and protective measures should consider various needs such as families, the aged, and individuals with disabilities. Hybrid contexts also enhance the applicability of wind and structural hazards as a result of temporary installations and may complicate evacuation since attendees do not always have a common purpose or compliance motivation.

Combined, storm-scenario typology and exposure-context typology would offer a rationale in the interpretation of the literature as well as in choosing adaptation strategies that are in tandem with predominant mechanisms. These typologies have been employed in the following sections to explain the variation of vulnerability and adaptive capacity drivers in different settings and the reason why the success of interventions in one setting may not be equally successful in another setting. The principal exposure contexts and their characteristic operational constraints are summarized in **Table 2**, providing a bridge between storm typology and the determinants of vulnerability and capacity.

Table 2. Exposure contexts for outdoor sport and leisure and their characteristic operational constraints.

Exposure Context	Exposure Geometry	Governance and Control	Shelter Availability Profile	Movement and Evacuation Constraints	Typical Weak Link in Storm-to-Impact Chain
Fixed venues (stadiums, fields, parks with defined zones)	High-density, bounded areas	Centralized authority is feasible	Variable; often uneven capacity vs. occupancy	Flow bottlenecks at entries, stairs, concourses; accessibility constraints	Execution delay due to congestion despite a timely decision

Table 2. *Cont.*

Exposure Context	Exposure Geometry	Governance and Control	Shelter Availability Profile	Movement and Evacuation Constraints	Typical Weak Link in Storm-to-Impact Chain
Linear-route events (marathons, cycling, triathlons)	Distributed along distance and time	Partial and delayed control across segments	Sparse and uneven; refuge varies by segment	Stoppage and sheltering are spatially heterogeneous; extraction logistics	Translation of warning into segment-specific protective action
Dispersed/remote recreation (hiking, climbing, camping)	Highly dispersed; terrain-driven	Individualized decision-making	Limited engineered shelter; reliance on natural features	Terrain traps; limited communication; delayed rescue	Risk perception and anticipatory planning failure
Water-based recreation/events (boating, paddling, surf, open-water)	Exposure on water; separation from shore	Mixed; organizers may have limited reach	Shore-based refuge only; "safe" zones depend on landing points	Exit may become infeasible once the squall arrives	Lead time insufficiency for safe recall/landing
Hybrid spectator–festival settings	High-density with heterogeneous goals	Shared/contested authority	Often temporary or mixed-quality refuge	High stimulus environment; movement disorder under urgency	Communication and compliance breakdown under uncertainty

4. Determinants of Risk: Vulnerability and Capacity Drivers

The presence of a hazard does not define risk in sudden storm events; in fact, it is created through the interaction of the characteristics of the hazard with the exposure, vulnerability, and adaptive capacity [62]. This interaction is particularly time sensitive in outdoor sports and leisure due to the need to take protective action and ensure that it is well within a small time frame. Risk determinants thus consist of both risk structural determinants that are characteristic of baseline susceptibility and risk dynamic determinants that determine the rate at which a system becomes aware of danger, makes decisions, and takes actions. This subheading is a summarization of the key factors that are causing vulnerability and resilience in environmental and infrastructural conditions, organizational and governance structures, human and social attributes, and information and communication technologies. It is aimed at explaining the reason why different settings can experience quite different consequences of similar storms, and why different adaptive strategies have to be aligned with the unique arrangement of determinants in the environment.

4.1. Environmental Setting and Micro Geography

Environmental setting influences risk in two ways: it determines the location of concentration of hazards, and the speed at which the state becomes dangerous [18]. In many cases, the terrain controls the exposure to lightning, wind, and floods in counterintuitive ways to those involved. It is the high ridges, the isolated mountains, the open lands, and water surfaces that enhance the risk of lightning exposure and wind exposure, whereas narrow valleys, arroyos, drainage systems of urban areas, and canyon systems can funnel floodwaters even when the rainfall is not directly on top of the area. The vegetation and the canopy structure alter the risk by creating branch-fall hazards and debris in the wind, as well as changing the ideas of safety. A tree canopy in most leisure venues can be construed as protection against the rain and consequently, protection against danger since it is more dangerous than a lack of shelter concerning falling branches, but offers minimal protection against lightning.

Protective action is also determined by microgeography. The distinction between a location that has many sheltered egress routes and one with a single narrow pathway, bridge, or stairwell can make the difference between an evacuation that is both quick and orderly and one that is congested and time-consuming. The coastal and riverine settings also bring on board other differences, like the riptides, enhancing the speed of a wave in a squall, and even the level of water, which can pin the victims against the landforms. The localized characteristics are critical determinants, as the abrupt storms tend to cause effects by localized amplification as opposed to an even spread of the conditions within a venue or region [63,64].

4.2. Built Environment, Shelter Quality, and Flow Capacity

A major factor influencing vulnerability and adaptive capacity is the built environment, since it determines the availability of shelter, protective performance, and the ability to move that is required to seek safety [65]. When in a fixed-venue environment, the existence of lightning-safe enclosed structures, surrounding activity areas, and capacity in comparison to peak occupancy has a strong influence on results in a lightning-dominant environment. The structural strength of both permanent and temporary structures is a focal point in wind-preferential situations, and the capability to attach and/or detach objects that may turn into projectiles within seconds. In case of heavy rainfall and flash-floods, the capacity of drainage, surface permeability, and the configuration of low points, underpasses, and channels affect whether water will be stored in harmful forms.

Shelter is something that should be seen in multi-dimensionality as opposed to binary. Convenient structure is not necessarily the one that will protect against the hazard in question, and the structure that is distant or inaccessible due to mobility limitations may not serve as a shelter in practice. The most common factor in a high-occupancy environment is flow capacity; the shelters may be within reach, yet it can take time to move large masses in and out, which is more than the available lead time. This is especially relevant to locations that have narrow entrance points, narrow walkways, small stairways, or accessibility restrictions, which slow down individuals of certain groups. Shelter distribution is also sparse and uneven in route-based situations, which puts more pressure on ad hoc sheltering, which might not be hazard-appropriate. With dispersed recreation, the engineered shelter might not be present at all, and the logic in place to protect shifts towards avoidance and timing in place of shelter entry [66,67].

4.3. Activity Characteristics and Exposure Dynamics

Various activities will impose varying exposure geometry, movement restrictions, and interruption tolerance, which characterize risk. Outdoor courts and field sports are often characterized by a high level of exposure in open spaces where lightning and wind risk is relevant, but the players often have time to halt in case authority is evident. Endurance events spread the exposure across space and time, and form portions at which the participants are far from shelter, and at which the stoppage becomes operationally challenging. Activities that take place in water increase exposure due to the decreased viability of immediate exit and augmented ramifications of sudden modifications in wind and waves. Mountain and backcountry activities enhance exposure due to elevation, isolation, and reduced escape routes, and decisions must be made long before any storms come [1].

Vulnerability is also determined by the intensity and duration of activity, whose physiological mechanisms are also influenced [68]. When one is fatigued, dehydrated, or suffering thermal stress, there may be a decrease in the capability to move rapidly, make correct decisions, and stay coordinated in the process of evacuation. Hail and cold-rain conditions may drive the participants to hypothermia, particularly when the exercise intensity drops suddenly during the stoppage. Exposure among spectators is not influenced by exertion but by density, mobility, and attention. Spectator-intensive situations may make people more vulnerable due to all three possibilities of remaining on the spot and underestimating the risk or not wanting to abandon a place, whereas evacuation could be hindered by congestion and the lack of exits.

4.4. Organizational Preparedness, Safety Culture, and Governance Maturity

Governance maturity is one of the key factors in determining whether warnings in the mechanisms of organized sport and managed recreation will lead to timely protective measures [8,69]. Preparedness consists of official policies, a specific level of authority in making the decision, training, exercises, and integration with meteorological and emergency services. Safety culture has an effect on how the policies are perceived as requirements of operation or optional restrictions that can be bargained under duress. In maturely governed organizations, it is common to set precise limits and logic of escalation, rehearse in a normalizing way, and design communication and staffing rhythms that can be used to take rapid action. Companies that have underdeveloped governance usually use informal judgment, blurred authority, or informal negotiation, which leads to longer decision-making and creates disjointed messages.

The authority has its most significant consequences in the case of sudden storms since the protective measures are in conflict with the game schedules, commercial demands, and social pressures [70]. When it comes to disputes over the authority to halt play or even order an area to be cleared, the protective measures are often seen in execution only when the hazards become visually clear, which leaves the time-to-shelter window possibly open by the time it is too late. Governance maturity also involves the capacity to run post-decision activities, which may include controlling re-entry, monitoring who has sheltered, the availability of accessible routes, and providing emergency access. In the case where they are not in place, the interruptions may pose new risks by creating congestion, confusion, or uncontrolled movement.

4.5. Information Systems, Monitoring, and Decision Triggers

When it is timely, relevant locally, and operationally interpretable, information is a determinant of capacity [71]. Examples of monitoring systems might be official weather alerts, radar-based nowcasting, lightning detection, a local observation network, and communication channels that provide messages to the staff and participants. Nevertheless, it is not the availability of information that is the determinant, but the usability. The usable information comes at a time when one can take action on it; it is framed in terms of certain actions, and people who receive it believe it. Operational feasibility-linked decision triggers, including time-to-shelter estimates, are ideal in facilitating more immediate and prompt actions compared to decision triggers with meteorological frames.

Capacity can also be compromised by the complexity of information environments. The participants are frequently alerted by various sources, not always with the same vocabulary or a similar sense of urgency, and this creates confusion. The forecasts are not guaranteed, prompting organizers to be reluctant to take action when such actions have already been made in the past with criticism. What may happen is the tendency to wait until a confirmation is obtained. Waiting is often a way of eliminating choices in the situation of sudden storms. Capacity is also enhanced when the organizations predetermine the decision triggers, make information sources clearer, and introduce redundancy so that the failure of one channel cannot lead to the failure of message delivery [72].

4.6. Risk Perception, Behavioral Response, and Group Dynamics

The outcome of executing protective actions in time relies on the behavioral factors, especially in the situation as long as compliance is not compulsory and authority is not a significant issue. Sudden storms [21]. Risk perception is influenced by cue visibility, past experiences, social norms, and perceived cost of interruption. Lightning and high winds may be ignored as a threat, only to be realized once they are imminent, and light rainfall may be thought of as the biggest danger, even when lightning or water runoff is the greater threat. Social proof is powerful; when other people are still active, it is viewed as a sign by the person that conditions are good. Caution may give way to identity and performance targets in a competitive environment. Persistence may be promoted by sunk costs in leisure situations, like traveling effort and limited vacation time.

Group dynamics have an impact on decision-making and movement. Families can be more focused on being together, which will make the evacuation slower but less prone to separation. The peer groups can go with the most assertive of them, irrespective of their level of expertise. Under the perceived urgency, crowds may act erratically, resulting in congestion and risk of falls. Protective action rehearsed and normalized, when instructions are unequivocal, and environments are structured to facilitate easy and socially rewarded safe actions, increases behavioral capacity. On the other hand, a decrease in the capacity appears when the messaging turns out to be ambiguous, when the action is not in line with the perceived incentives, and when the protective options become unrealistic [73].

4.7. Equity, Accessibility, and Differential Vulnerability

Equity is a cross-cutting determinant since the capacity to act in case of sudden storms is not equally distributed [74]. Limitations in mobility, sensory, and language barriers, and the lack of familiarity with the hazards prevalent locally are issues that can make a person more vulnerable, particularly during rapid evacuations. In cases where the separation procedures are not explicit, children may rely on the conclusions of adults and could be segregated in school or camp settings. Elders can be prone to falls when in a rush and can be prone to thermal stress. Tourists and visitors might fail to identify which local clues to use in storm development, or they may not have access to reliable sources of information. Socioeconomic aspects may affect the ability to use appropriate equipment, navigational equipment, and communication equipment in dispersed recreation.

Accessibility also overlaps with infrastructure and governance. Technically safe shelters might be functionally inaccessible due to the use of stairs, uneven surfaces or the lack of wayfinding. The communication cannot reach non-native speakers or those who do not have smartphones. The processes that presuppose quick and equal mobility may unwillingly put vulnerable groups at a greater risk. A proper risk evaluation must thus involve not just identification of hazard but also the clear listing of who is capable of comprehending the protection measures and what will have to be done to ensure that all get to be safe [18].

4.8. Emergency Response Capacity and Consequence Amplification

Response capacity defines the degree of results in case of failure of preventive measures or incomplete preventive measures [75]. In controlled locations, medical teams on-site, quick access capability to emergency services and trained incident command can mitigate the severity of consequences. Conversely, in remote recreational environments, the response can take long periods and even survivable injuries in urban environments can be fatal because of the delay in care and environmental contact. Even weather can be a hindrance to rescue, especially in the case of wind, heavy rains or floods. Response capacity is an aspect of vulnerability: it is the determination of how far hazard exposure will go to extreme consequences.

Cascading failures also have an effect on consequence amplification. Public address systems, lighting and electronic gates may be ineffective due to a storm that interrupts power, which may make movement and communication difficult. Floods may block access roads to the emergency vehicles. The destruction caused by the wind may leave debris areas that impede evacuation. These cascades point out that adaptive capacity is made up of not just the initial protective measures, but also resilience to partial infrastructure failure [76]. **Table 3** shows the important determinant domains and provides operational indicators that can be measured to diagnose weak links in storm readiness and response.

Table 3. Determinants of vulnerability and adaptive capacity with example operational indicators.

Determinant Domain	What It Changes in Practice	Example Operational Indicator (Measurable)	Why It Matters during Sudden Storms
Microgeography and terrain	Where hazards concentrate and where people get trapped	Presence of flood-prone low points on route; exposed ridgeline segments; shoreline distance to exit	Impacts are often localized and develop faster than people can relocate
Shelter performance and accessibility	Whether "shelter" is actually protective and usable for all	Percentage of peak occupancy accommodated in hazard-appropriate shelter; accessible time-to-shelter for mobility-limited users	Safe outcomes depend on feasible, inclusive refuge within the lead time
Flow capacity and egress design	How long does it take crowds to reach refuge	People-per-minute throughput at key entry points; observed congestion duration	Congestion extends exposure and creates secondary injury risk
Governance maturity and authority	Decision speed and consistency under pressure	Documented decision roles; proportion of events with trigger-based decisions	Ambiguity increases latency and inconsistent messaging
Monitoring and trigger usability	Whether information arrives early enough and is interpretable	Monitoring coverage continuity; trigger-to-action initiation time	Information is protective only when it produces timely action
Communication reach and comprehension	Whether instructions are received and acted upon	Message reach rate; comprehension checks; multilingual coverage	Compliance depends on clarity, credibility, and inclusive delivery
Behavioral norms and incentives	Willingness to stop activity and shelter early	Observed compliance rate; delay between message and movement	Social proof and sunk costs can delay protective action
Response capacity and access	Severity of outcomes when prevention fails	EMS access time; rescue feasibility under storm conditions	Consequences amplify where rescue is delayed or blocked

4.9. Interactions and Context Dependence of Determinants

The determinants mentioned above can hardly work alone. Lack of clarity of authority can terminate high-quality monitoring; lack of clarity of shelter can terminate good-quality monitoring; lack of quality monitoring can terminate adequate flow capacity, and lack of good flow capacity can terminate well-crafted procedures [77]. Most significant interactions are most likely to happen when there is a time constraint, where any slight delay is multiplied by considerable exposure. The role of context dependence is thus high: what works well in a fixed location with lots of shelter may not work well in a linear-path event with very little shelter and distributed participants, and vice versa, may also not work in dispersed recreation in which there is no central control [78].

Knowledge of these determinants is the basis of matching the strategies of adaptation to the actual failure modes. This review then (in the following section) maps strategies to mechanisms in the storm-to-impact chain and to the typologies of storm situations and exposure circumstances, focusing on feasibility, trade-offs, and under which circumstances strategies would tend to bring about significant risk reduction.

5. Adaptation Strategies Mapped to Mechanisms

5.1. Forecasting Integration and Situational Awareness as Enabling Capacity

The situational awareness measures decrease the risk by enhancing the timeliness and relevance of the hazard information and enhancing the conversion of meteorological signals into operational meaning [79]. Usually, in structured sport and controlled leisure environments, it entails the incorporation of forecast and nowcast products into daily activities, the establishment of monitoring responsibility, and linkage with meteorological organizations or local authorities. It is not merely earlier detection that causes the mechanism: when the monitoring is continuous and interpreted on the basis of locally meaningful events, protective decisions are possible before the hazards are manifested to those being monitored or the audience.

Spatial and temporal resolution are important determinants of the utility of situational awareness [80]. Events that rely on routes and scattered recreation need more detailed awareness, as hazard conditions may vary both within a section of a course and within microgeographies. Within such environments, operationally useful information that may be able to point to localized storm development, rapid runoff possibility, or wind change is better than generic warnings. In water activities, the awareness should focus on the rapid change in wind and the formation of squalls, since the action window of protection can be closed as quickly as possible when the wave conditions get out of control. In every environment, source redundancy is a constituent of resilience; when one source fails or one product is unclear, there is still the option to triangulate risk. Situational awareness, however, is also associated with the problem of information overload and conflicting signals. The process of adaptation, however, involves not merely the acquisition of more data but rather the development of interpretive routines and hierarchies which transform data into transparent operational judgments.

5.2. Decision Thresholds, Stop Rules, and Authority Models to Reduce Decision Latency

Governance strategies in decision-making involve minimizing the risk of ambiguity regarding the decision maker, the time of decision, and post-decision activities [81]. One of the key mechanisms is the implementation of pre-established thresholds and the stop rules, which connect the observed or predicted conditions to protection measures. These rules serve as time-saving mechanisms in sudden storm situations: they minimize the amount of negotiation necessary in time-pressed situations and enable uniformity of message. Their practical usefulness will depend on the fact as to whether they are to be designed for functionality in action, and, in that regard, on time-to-shelter, movement capacity, or meteorological criteria, by themselves. A technically accurate and operationally late threshold does not minimize exposure.

Thresholds are enforceable based on authority models. In most sports environments, there are delays that come about due to the decentralization of decision rights or a lack of accountability. Explaining the authority may reduce the time that can be spent before action is initiated once the hazard has been identified, and this is increased when combined with rehearsal of what each position entails once a stop decision has been made. Also, in mass participation events, governance should consider the distributed control; the organizers cannot stop all participants immediately, and therefore thresholds have to be accompanied by staged control mechanisms, route marshaling, and steering towards the nearest safe places. In informal recreation, power is curtailed, and hence, the decision-making governance is redesigned, as guidance to facilitate individual decision-making. In this case, a similar adaptation measure would be the establishment of clear heuristics and route planning standards, which would promote the early prevention of exposure points in the case of storm potential [82].

Stop rules should be formulated in a way that they maintain safety in various hazards. Any approach that provokes a move to a lightning shelter can also cause an unwanted exposure to wind or flooding in case the routes get into dangerous territories. Strong governance thus extends to the escalation logic, which separates the currently used sheltering in place, controlled evacuation, rerouting, and termination, based on the type of hazard scenario. It also has the re-entry and resumption criteria, which ensure that one does not go back to the exposed places too early in case there is still lingering lightning risk or unstable wind. The maturity of governance is indicated by the fact that these determinations are specified, practiced, and made in terms that the participants are able to comprehend and approve [83].

5.3. Built Environment Adaptations: Shelter Performance, Accessibility, and Hazard-Compatible Design

The reduction of risk in infrastructure strategies occurs by altering the physical limitations that define the possibility of the protection actions within the time available [84]. Within permanent locations, the most direct process is the augmentation of hazard-suited shelter and the accessibility of shelter, which must be recognized as adequate to accommodate the maximum number of users. This normally means enclosed buildings with protective features in the case of lightning and a refuge that is resistant to structural forces and safe against debris in the case of wind. The physical effectiveness of shelter is influenced by the capacity and flow. Even a quality shelter cannot mitigate risk when it has bottlenecks of entry, dispersing the exposure, or when available routes are not sufficient to accommodate all the users.

Lacking any control over the weather conditions, which is characteristic of storm conditions filled with large amounts of precipitation and flash flooding, built environment modifications are directed at drainage, routing, and removal of trap hazards [85]. The high rate of accumulation and hazardous streams during crossing zones can be avoided by enhancing drainage and minimizing the concentration of runoff. The adaptations to infrastructure in route things can be less about the construction of new shelters, as well as the choice to use routes that are free of known flood areas, and the course construction incorporating safe refuges and possible extraction areas. Physical controls, such as signs and barriers that do not allow access to flood-prone canyons or channels during the event of a storm, may be used as infrastructural management in managed recreation areas since they can modify exposure pathways.

Temporary buildings are one of the unique weaknesses of hybrid sport-leisure events and festivals [86]. In this case, some of the areas of adaptation include wind resistance engineering and procurements, anchoring, inspection, and fast-securement. The process is to minimize the likelihood of a wind event causing high-energy debris, and structural collapse. Since the sudden onset of the wind can exceed the capability to stabilize structures, resilience can be a combination of structural resilience and early decision indicators to prompt operators to take defensive measures prior to the onset of the winds. Wayfinding and lighting are also part of the built environment across contexts and have the impact of influencing movement safety in the presence of precipitation and reduced visibility. Such features are especially necessary in cases when storms occur on the evening, or when power outages are possible.

5.4. Operational Planning and Incident Management for Coordinated Execution

The operational strategies minimize risk through enhancing the execution speed, coordination, and safety of the protective actions [87]. This, in organized situations, covers incident management arrangements, staffing, training, and drills that render protective activities standard instead of ad-hoc. The idea is to make the action less frictional: once roles are recognized, routes are followed by the same route, communications are memorized, the defensive measures can be implemented within a short period, and executed in the same manner. Other complications, such as crowd congestion, risk of separation, as well as medical complications during evacuation and accessibility requirements, are also the expectations of effective operational planning.

In the case of a fixed location, operational planning entails mapping the areas of shelter, staffing these areas to direct traffic, keeping emergency access lanes, and ensuring there are policies to deal with a controlled re-entry. In the case of route-based events, the distributed nature of exposure will need to be planned by determining how to stop participants at multiple locations, how to transport them to the closest safe position, and how to provide transportation/shelter when participants are distant to start/finish points. In the case of water-based operations, operational planning contains rapid recall procedures, safety craft preparation, and definite termination criteria that emphasize leaving prior to conditions becoming irreversible. Operation planning in the context of dispersed recreation is frequently part of land management and outdoor programming, not participant-oriented; it may be through educational programs, trailhead education, seasonal closure of risky places whose safety is under convective potential, or the creation of rescue coordination guidelines that are conscious of access limitations during storms [88].

In any situation, operational planning should consider the potential that any protective action, in a poorly conducted manner, will create additional risks. Lightning evacuation may cause crowding in partially sheltered areas, whereas wind evacuation may expose individuals to falling debris. Scenario-based rehearsal of planning, therefore, helps to match the protective action with the type of hazard, which is not to assume that all storms must be moving in the same direction. This alignment is also an adaptation by itself since it avoids the strict following of one playbook when the dynamics of hazards require alternative decisions [89].

5.5. Communication and Message Design to Support Comprehension and Compliance

Strategies of communication minimize risk by enhancing the chances of people comprehending what is going on, believing the message, and responding to the intended action promptly [90]. Shortening the time taken between receiving messages and movement to safety is the critical mechanism in sudden storm settings. Messages that are advisory or vague can enhance deliberation, and messages that have specific action, destinations, and urgency may facilitate immediate compliance. Channel redundancy and segmentation of the audience are also important to communication effectiveness. The participants, spectators, staff, and surrounding bystanders may require various information, which is to be communicated in various channels, at varying times.

At regular locations, communication may take advantage of loudspeaker systems, display screens, employee signs, and notifications via mobile phones. The difficulty is to make certain that there is consistency between channels, particularly when external alerts and internal instructions come at the same time. In route-based events planning, delivery can be compromised by coverage lost, and device variability; mobile alerts and communication between marshal and participant are brought more to the center. In dispersed recreation, there is limited connectivity and communication is limited by the fact that most messages are given before exposure has commenced. In this case, the pre-activity communication at the trailheads, rental points, program briefings, etc., turns critical, and messages should be based on the anticipatory decision, not evolving in the moment, for evacuations.

Equity cannot be disregarded in message design. The determinants of whether protective actions can be available to all the participants are multilingual delivery, access to sensory impaired formats, and instructions based on mobility limitations [91]. Trust is also developed through communication. In preemptive decisions, explanation in briefs relating the action to the hazard may reduce frustration and enhance future compliance. On the other hand, the continuous disruption without a clear explanation may lead to loss of trust and promote a risky wait-and-see attitude. Adaptation thus comprises refinement of messaging through feedback on the detected understanding and pattern of movement in the context of previous events.

5.6. Behavioral Capability and Training: Shifting Norms toward Early Protective Action

Behavior approaches diminish the risk by altering the perceptions and reactions of people to the storm signals and safety measures [92,93]. In structured athletics, such training that conditions high rapidity of termination and protection can lessen the opposition and disorder in real life. Repetitive exercises act as a mental shortcut in times of stress: once the participants and the staff know what to do, they do not need to spend as much time interpreting or arguing. Repeated drills may be especially protective in youth sport and school situations because children rely on adult coordination and may be susceptible to the effects of separation and panic in the event that the procedures are new.

Behavioral capability can be the main modifiable factor in leisure and dispersed recreation, where the lack of infrastructure and centralized control restricts the opportunities [94]. Anticipatory planning, understanding of the schedule of routes, identifying the signs of a storm, and avoiding terrain traps can be used to reduce exposure before hazards become acute in education. Notably, a successful education does not depend on the description of hazards but rather relates hazards to decisions. To provide an example, the most critical protection action in flash-flood risk is to avoid particular landforms at the time of convective potential, and not to take shelter once the water level escalates. In the case of water-based squalls, early returning to shore is the protective behavior rather than waiting to observe the strengthening of winds. Social norm shaping is also part of behavioral adaptation, e.g., framing early withdrawal as competent decision-making instead of failure, which is particularly relevant in a competitive culture or the adventure culture.

5.7. Policy, Liability Environment, and Standardization as Structural Supports

Storm safety is affected by policy and standards, which have an impact on the incentives and minimum preparedness expectations in organizations [95]. This is an indirect and strong mechanism: when the standards elucidate the duty-of-care expectations, specify the minimum monitoring and response requirements, or mandate documentation of decisions and incidents, organizations tend to invest more in the capacity and implement the thresholds consistently. A liability environment, on the other hand, which rewards interruptions or causes ambiguity regarding acceptable risk, may push decision-makers into delayed action. Interoperability may also be enhanced under standardization between the event organizer and local emergency services to enable them to agree on terminology, escalation, and communication procedures.

The reality is that the policy-based adaptation will have to face the heterogeneity in size and resources of the organization [96]. Large facilities and professional organizations can employ professional safety personnel and have well-developed infrastructure, whereas community activities and informal recreation providers can have limited capacity. An effective policy solution in this regard would thus appreciate the idea of tiered expectations: minimum requirements that small operators can easily meet, with higher requirements in high-occupancy or high-exposure settings. There is also standardization in the reporting. Learning will be a matter of chance without regular recording of the near-misses, stoppages, and evacuation performances. Evidence base can be enhanced with policies that promote or mandate systematic reporting and help with ongoing improvement.

5.8. Evaluation, After-Action Learning, and Performance Measurement

The long-term risk reduction is achieved through learning strategies, which help to determine weak points in the storm-to-impact chain and transform experience into better procedures and designs [97]. The feedback mechanism can help identify the presence of monitoring timely, the application of thresholds, message interpretation, and movement bottlenecks through the after-action reviews, incident debrief, and near-miss reports. Process metrics are critical in sudden storm situations when severe injuries might be few compared to the number of breaks and almost misses. Time-to-decision, time-to-shelter, message reach, observed compliance, and congestion points are some of the measures that can be tested even in cases where catastrophic outcomes are not realized.

Thresholds and communication practices are also to be calibrated with the help of evaluation. When a specific organization causes repeated stoppages with low perceived relevance, it is possible that trust could be undermined, and triggers should be improved, or better explanations should be offered. In the event of congestion in evacuation routing or capacity in a shelter, it may require redesign. During route-based events, analysis can identify areas of the route where participants lack options to take refuge in, and adjustments to that route can be made. Evaluation in dispersed recreation programs can help dispel the misconception about local hazards to direct the education focus. Through systematic learning, storm safety initially can be viewed as reactive improvisation in response to a storm, but over time, storm safety can shift towards adaptive resilience, wherein interventions are constantly adjusted to the observed modes of failure and to changing patterns of participation [98]. To emphasize the portfolio logic of adaptation, **Table 4** maps strategy classes to specific storm-to-impact chain links, context relevance, implementation barriers, and practical evaluation signals.

Table 4. Adaptation strategies mapped to storm-to-impact chain links, context relevance, barriers, and evaluation signals.

Storm-to-Impact Chain Link Targeted	Strategy Class	Most Relevant Contexts	Primary Mechanism for Risk Reduction	Common Implementation Barrier	Practical Evaluation Signal
Hazard monitoring and interpretation	Integrated nowcasting, lightning detection, local situational awareness	All, especially route-based and water-based	Increases actionable lead time and reduces surprise onset	Information overload; unclear source hierarchy	Earlier trigger activation without loss of credibility
Decision and authority	Stop rules, trigger thresholds anchored to time-to-shelter, clear decision rights	Fixed venues; organized events	Reduces decision latency and inconsistency	Commercial/competitive pressure; unclear accountability	Reduced recognition-to-decision time; fewer late evacuations
Protective action feasibility	Shelter capacity upgrades, accessible routing, wind-safe temporary structures, drainage design	Fixed venues; hybrid events; managed sites	Makes safe action physically possible within the lead time	Cost; space constraints; retrofitting complexity	Reduced time-to-shelter; fewer bottlenecks; improved shelter utilization
Communication and compliance	Redundant channels, action-oriented scripts, multilingual/accessibility design	All, especially spectator-heavy and dispersed	Converts decision into rapid, understood behavior	Message inconsistency; trust erosion; device/connectivity limits	Higher reach and comprehension; faster movement initiation
Learning and calibration	After-action review, near-miss reporting, performance dashboards	All	Improves future performance by identifying weak links	Underreporting; lack of taxonomy; "no time" culture	Documented corrective actions; measurable improvements over time

As a whole, the sudden storm risk adaptation strategies work in a limited number of mechanisms: enhancing actionable lead time, lessening decision ambiguity, improving shelter and movement viability, improving message understanding and credibility, facilitating compliance, and embedding learning. The performance of any strategy relies upon the degree to which it is appropriate to the prevailing storm situation and exposure condition and on the presence of a consistent system to which the strategy is integrated to fortify numerous connections of the storm-to-impact cycle. The subsequent section puts these classes of strategies into both implementation considerations and evaluation priorities, keeping in mind the scalability across the resource levels and the tradeoffs that occur when safety choices collide with participation, economics and equity.

6. Implementation and Evaluation: From Guidance to Practice

The implementation process is where the conceptual models and recommended strategies fail or become protective capacity or a dream. Sudden storms require adaptation efficiency to operate within short and uncertain timeframes and remain safe in relation to a variety of hazards [98]. The section explains the way storm-risk measures can be operationalized at multiple levels of resources and exposure settings and how the evaluation may be designed in such a way that it encourages ongoing improvement. The focus is on the translation of the adaptation mechanisms into the procedures, infrastructure decisions, communication patterns, and quantifiable performance measures which correlate with the storm-to-impact chain. As shown in **Figure 3**, implementation can be organized as a portfolio of controls aligned to chain links, with process metrics that support calibration and continuous improvement.

6.1. Implementing Tiered Preparedness across Settings and Resource Levels

There is great diversity in outdoor sport and leisure systems in terms of staffing, budget, and infrastructure, and therefore, implementation is facilitated by a tiered preparedness model bringing up scaled expectations [99]. On a low-tech level, minor organizations and even community meetings can establish the existence of distinct authority in decision-making, regularity in monitoring duties, and pre-written communication instructing individuals on where to congregate and what to do in the event that activity is suspended. The realistic accounting of shelter options, their protective measures against the relevant hazards, and an estimate of time-to-shelter of the most exposed groups also make up baseline preparedness. Practically, this lower level is not as much about obtaining advanced technology, but rather is more concerned with eliminating ambiguity and latency in the decision and action chain.

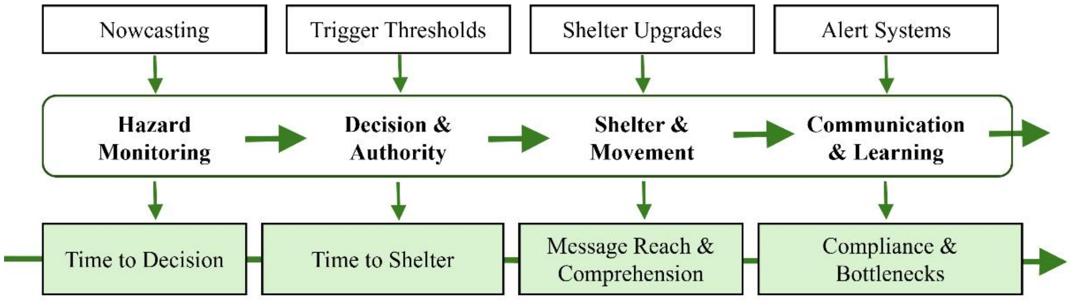

Figure 3. Adaptation portfolio aligned to storm-to-impact chain links with evaluation metrics.

The increased exposure density or the complexity of the situation leads to the necessity of enhanced preparedness. Mass-scale events, high-pressure venues, and large tournaments are the events that usually have redundant monitoring sources, formal logic of escalation, and staffing that is capable of addressing the needs of movement and accessibility. In the case of route-based events, one of the improvements to preparedness is segment-level planning, which includes finding refuge points, closures, or reroutes to known hazard traps (such as flood-prone corridors) and communication plans to reach participants who are widely spread. High-reliability preparedness is most appropriate in environments where there is extremely high occupancy, extremely high consequences of failure, or even extremely high limitations on the movement of protection, as is the case with large stadiums, large festivals, and elite events. These settings may even be implemented to formal incident command integration, special safety officers, and engineered movement controls that enhance shelter capacity and movement flow[100].

At all levels, the viability has to do with the compatibility of the preparedness package with the most frequent storm conditions. As an example, a place that is centered around lightning measures can still be susceptible to wind-blown debris in case temporary constructions are prevalent. An event with strong weather monitoring can be vulnerable to flash flooding when the route selection and route closures are not incorporated in the plan. The tiered model is therefore most effective when it is scenario-specific so that the investments are made in response to the most likely and probable hazards in the setting[101].

6.2. Operationalizing Decision Triggers and Escalation Logic

Decision triggers and escalation logic can only be protective in cases where they are operationally interpretable and associated with actions that can be executed. This is implemented by initializing triggers that are based on time-to-action, and not on hazard detection per se. This, in reality, needs to be estimated in terms of the time needed to pause activity, establish instructions, and transport individuals to a hazard-suited shelter, even with mobility limitations. Such triggers can then be tuned to make decisive action early enough so that the protective measures can be taken before the conditions are critical. In a lightning-dominated situation, this can be taking action when the threat is near as opposed to taking action when the threat becomes visible. In wind-dominated cases, it could imply taking measures at a confidence level adequate to act in taking precautions in order to ensure that structures are not left uncovered and exposed to debris, as once the winds are getting into the act, the pool of protection possibilities shrinks rapidly. In case of flash-flood risk, triggers have to be spatially sensitive, since the most hazardous situations can be observed in particular corridors instead of throughout the entire venue or route[102].

Escalation logic has a relationship between triggers and graded actions, which indicate the severity of the hazard as well as the feasibility of operations. The definition of actions being associated with increased monitoring, staff pre-positioning, pre-emptive communication, suspended activity, controlled sheltering, evacuation, rerouting, or termination is useful in implementation [103]. This reasoning should be able to fit into multi-hazard realities. In case lightning is predicted with a storm that will lead to heavy rain, one should look at the escalation in advance, considering that the places where the lightning can be safe might become problematic when there is a runoff around the area. Equally, when there is a possibility of wind and debris, evacuation paths traversing the fields might not be secure, and the focus should shift to taking refuge in sturdy structures. The main implementation issue is not to take the cat-in-the-middle approach and respond with strictly one-size-fits-all procedures by making procedures hazard-conscious.

Authority frames are part and parcel of trigger implementation. Plans with triggered plans but no specifications on who declares a stoppage, who initiates communications, and who controls movement, will still have delay problems under pressure. A rule thus becomes effective as the way in which decision-makers access information sources, the way in which the ruling is recorded, the way in which it is disseminated, and executed. In dispersed settings and route-based settings where enforcement is weak, the implementation is centered on making the guidance practical to individuals, which involves straightforward directions that represent the terrain and areas of refuge locally.

6.3. Building Communication Systems That Work under Stress and Uncertainty

When communication lessens the cognitive load and facilitates quick action, communication is operationally successful. Channel design and message design are needed to implement. The design of the channels focuses on redundancy and reach; many pathways can be used, and they can be operational even in case one of them fails, and messages can be delivered to the participants, spectators, and staff in parallel. These can be public address, screens, staff signaling, and mobile notifications in fixed venues. Mobile alerts and marshal relays are the focus of route-based events, though implementation should expect inconsistent connectivity, device settings, and user attention. The communication in dispersed recreation is also front-loaded, which depends on the signs at the trailhead, rental briefings, program orientations, and pre-trip planning materials, as real-time alerts may be inaccessible to people after they have gone to remote locations [104].

The impact on the design of a message determines whether the communication will result in compliance. The instructions to be implemented should focus on those that govern the hazard using simple language, state the immediate course of action, and the destination or the safe behavior without interpretation. In uncertain situations, communicating in a manner that admits uncertainty and yet gives direction may save face. In case early interruptions are more tolerable when people realize that there is action being taken, since the safe window of movement is constrained. The considerations of accessibility and equity during implementation also entail the use of multilingual delivery, visual and auditory redundancy, and instructions that are realistic to people with limited mobility. Given that communication systems are not designed to consider such needs may inadvertently increase the gap in vulnerability, although they may be working well with most people [105].

Re-entry and resumption messaging should also be part of the communication in an organized setting, since misunderstanding at this stage may lead to premature movement back to the exposure or circular movements without control [106]. When re-entry is seen as a process with clear criteria and stage flow, implementation is more effective instead of an informal process of returning to normalcy. Consistency strengthens the reliability of communication over time; the participants who receive messages that conform to the observed conditions and result in safe outcomes develop trust, which enhances compliance during future storms.

6.4. Integrating Infrastructure and Movement Planning into Operational Readiness

Infrastructure and movement planning can be reduced to risks only when the two are combined into procedures and regularly tested [107]. It is implemented by first conducting a shelter inventory, which determines the protective performance and capacity, and establishes the difference between peak occupancy and accessible safe space. This is a fixed venue that involves examining flow capacity in entrances, concourses, and stairwells and determining whether available paths can serve all users during periods of time stress. In cases where capacity or access is inadequate, physical modifications may be needed, e.g., better wayfinding, barriers preventing unsafe crowd rushes, or creating areas where multiple shelters can be so that there is less of a bottleneck.

When dealing with wind and debris hazards, the implementation is usually done through procurement criteria, inspection schedules, and the ability of the staff to secure or to remove the temporary structures. The viable experiment is whether such measures can be accomplished prior to the onset of wind, which in its turn is conditional on the triggers and staffing. In extreme rainfall and flash-flood-prone areas, the implementation of infrastructure should involve finding and controlling hazard traps in the form of underpasses, tight channels, and low-lying collectors, and the creation of closures or other reroutes that can be opened as quickly as possible. The benefits of route-based events are that they include segment plans that take into account the way to stop the participants, where they can be sheltered in case of extraction if movement becomes unsafe [108].

Safety control is also movement planning due to evacuation, which can be dangerous in itself[100]. This should be implemented with scenario-based movement design, with the protective action being aligned with the prevailing hazard. The lightning-related situations, where quick traveling to the enclosed shelters is suitable; the lightning-related situations, where traveling through the exposed areas can cause more harm; and the lightning-related situations, where traveling to higher places and staying out of channels is crucial, are identified. The consideration of the movement as a risky operation is one of the reasons preventing the widespread failure to implement a single evacuation script, irrespective of the type of storm.

6.5. Designing Evaluation around Chain Performance Rather Than Rare Outcomes

Sudden storm risk management cannot be assessed only based on the number of injuries or deaths, since serious consequences are quite rare and are not always reported or classified differently [109]. Evaluation implementation is therefore advantageous in the consideration of performance throughout the storm-to-impact chain. Process measures offer practical information about the success of interventions, even in the event of zero injuries. Such steps are the timeliness of recognition of the hazard, the delay between hazard recognition and decision, the delay between decision and receipt of messages, the share of the population reached through messages, perceived understanding and adherence, and time taken to get to the shelter or safe state. In venue settings, it is possible to measure flow patterns and bottlenecks by staffing observation, review of the camera, or an analysis by simple counting at major release points. In route-based events, measuring can be done based on the time-to-shelter distribution by course segments, whether the marshals can halt participants, and how well the segment closures of flood-prone regions are successful.

Quality review also involves the evaluation of whether there was hazard-appropriateness in the decisions made [110]. When an action fails to match the situation, there is an indication of a stoppage that causes people to be exposed to wind or subject to a potential of flood. Equally, recurring disturbances using no clear justification may damage trust, compromising future adherence, which is an assessable effect though not necessarily resulting in immediate harm. In the case of dispersed recreation programs, assessment may be focused on modifying the planning behaviors of participants, terrain trap awareness, and compliance with timing recommendations, with recognition that much of the protection decision-making takes place before an exposure.

6.6. Institutionalizing Learning through After-Action Review and Near-Miss Systems

When the learning process is institutionalized instead of being reliant on individual memory, it becomes permanent. Learning systems are approved by initiating the regular after-action review after storm-based disruption, even in cases of benign results. These reviews are the most informative when they concentrate on chain performance, and they have many points of view, and such points of view include the operations staff, medical teams, communications personnel, and, as much as possible, participant feedback. The production must be directly converted to triggers, messaging, staffing, shelter plans, or infrastructure priorities [111].

Near-miss reporting also happens to be very useful since it is used to record situations where damage was just avoided, and this gives an insight into areas of vulnerability without necessarily causing disastrous results [112]. But the near-miss systems need to have a common taxonomy and a non-punitive culture, or there will be less and biased reporting. The implementation would thus involve the definition of what is meant by a near-miss in storm situations, simple reporting measures, and the review and action on the reports. This type of documentation of stoppages caused by the storm, timing, warning signs, activities undertaken and movement problems observed could accumulate over time, creating operational data that generates improvement of thresholds and processes in most settings.

6.7. Addressing Trade-Offs, Equity, and Sustainability of Practice

The implementation must always face the trade-offs between safety, continuity, and cost [34]. Protective decisions may have an economic impact on events and destinations, and frequent disruptions may inhibit satisfaction and attendance. But, trying to reduce inconveniences, postponing action may expose people to high-consequence risks. A sustainable practice model thus addresses trade-offs as explicit in assigning protective measures to specific and clear criteria and by articulating the rationale in ways that will preserve trust. When the stakeholders can be convinced that safe sheltering may only be viable when taken at an early stage, the discharges can be seen as a sign of good management and not an overreaction.

Implementation and evaluation should be done with references to equity instead of being handled as a post-facto [113]. Movement and information access should be made heterogeneous, and shelter and movement designs should be rated on accessibility under time pressure. The communication process should be inclusive in nature, and personnel training should involve the perception of the impact that evacuations have on various groups. Sustainability also requires the avoidance of paper plans that are not rehearsed. The readiness is maintained through periodic drills, staff refreshers, and the updated version developed through observations. Sustainability in informal recreation aspects incorporates the presence of consistent public messaging as well as making sure that the educational material is updated and locally applicable.

Combined, implementation and evaluation turn adaptation into a guide to operational resilience. Strongest systems are the ones that match monitoring, triggers, authority, communication, shelter, and learning in ways that the protection actions are taken early enough to make a difference and are done safely among a variety of parties and hazard situations. The conclusion that ensues summarises the implications of this review and sets priorities that can be implemented to enhance the safety of sudden storms in outdoor sport and leisure.

7. Conclusions

Outdoor sporting and leisure activities have a unique and consequential risk due to sudden events of storms, since time constraints to act on the risk are often condensed, and the risk can often assume complex hazards dynamically developing in space. The evidence, which is synthesized in this review, confirms one major premise: that adverse outcomes are hardly ever the result of meteorology only. Rather, the harm and disruption arise whenever the suddenly evolving hazards are combined with high exposure, a lack of shelter viability, weak decision control, and delays or failure of communication and coordinated movement. The socio-technical systems approach to sudden storm risk, instead of focusing on it as a forecasting issue in an isolated context, offers a more straightforward foundation to research synthesis and practical adaptation.

In storm situations, there exist more regular patterns in the processes of converting weather into effects. Situations where lightning is dominant in particular reveal the significance of action prior to things seeming to be too serious, since visual confirmation is often too late to get to the safety of scale. The susceptibility posed by temporary structures and the fact that evacuation can even be dangerous in case of wind- and debris-dominant events, because routing operations will involve exposed surfaces. Flash-flood situations highlight the importance of spatial particularity and terrain-conscious planning because the most hazardous situations are frequently directed in corridors and may not correspond to apparent rainfall intensity where it happens or exposure. The squalls on water emphasize the fact that the area of protection can rapidly be closed once the wind and waves surpass the ability of the participants to recuperate, especially when those people are new. These differences between scenarios support the importance of adopting protective measures that are appropriate to the hazard mechanisms and not to the use of the same procedures for all storms.

Determinants of vulnerability and capacity reported in this review highlight the nature of safety performance, which is influenced by the changeable elements of operations. Effective ingress scenery not only ought to be danger-fit, but reachable and accessible during the allocated time bandwidth; however, in overcrowded environments, circulation ability can end up acting as the restrictive determinant. Governance maturity, in terms of definite authority, thresholds associated with time-to-shelter, and practiced procedures, minimizes the time to a decision and provides a uniform course of protective response in the face of uncertainty. Redundant, action-oriented, inclusive, and realistic movement communication is most protective and contributes to trust and compliance. Equity is part of them and not peripheral: the idea of differential mobility, access to language, knowledge of local hazards, and access to timely information is what determines who will get the protection measures and who will not be adequately covered.

The best adaptation strategies are those that are adopted as a consistent set that brings about numerous storm-to-impact chain links. Better monitoring and nowcasting are facilitating the ineffectiveness unless thresholds are not clear or shelters are not sufficient. In the same vein, good infrastructural support of shelters would not offset the slowness of decisions or the lack of consistency in messages that do not jump-start action in time. A properly functioning practice hence lies in aligning the system: sustained scenario perception in the form of transforming the new situation into the form of local triggers; authoritarian arrangement that is wary of decisive action; mobility and refuge plans that take into account the disposition capacity, accessibility and Threat compatibility; and learning plans that ensure procedures are refined in the form of post-incident method examination and second miner misadventure records. Chain performance measures (time-to-decision, time-to-shelter, message reach and comprehension, and observed bottlenecks) should be given higher priority in evaluation methods since serious outcomes are rather rare and inconsistent injury statistics cannot be effectively used to draw credible conclusions about intervention performance.

Priorities of future research and setting standards are also identified in this review. There are still very few comparative assessments of the effectiveness of the intervention, especially in communication designs, threshold calibration, and route-based or dispersed situations, where the effect of a centralized control is limited. It would be more standardized to report cases of storm-related disruptions, near-misses, and operational performance that would allow more synthesis and enhance the transferability of lessons between settings. Blending of human factors with infrastructure and decision support design research is particularly required since compliance and movement dynamics frequently dictate the success of protective measures within the short time available. Lastly, the impact on various groups of participants of storm-risk policies and practices and the potential to reduce disparate vulnerability through inclusive design of shelters, messaging, and procedures should be researched using an equity perspective.

The practical implications in question can best be summed up, and its significance to sudden storm safety most effectively enhanced, by a small number of high leverages: taking into practice hazard-conscious triggers pegged on time to shelter; creating clear authority and escalation logic; providing sufficient, accessible, hazard-appropriate shelter and movement capacity; communicating clear, redundant, inclusive messages specifying what it entails; and formalizing learning by means of routine after-action review and near-miss systems. These aspects will need reinforcement to safeguard participants and spectators, maintain confidence in outdoor programming, and ensure the continuance of the societal and health benefits of outdoor sport and leisure in case of an abrupt storm threat, as outdoor participation increases and the nature of the event becomes more complex.

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