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REVIEW

Assessing the Vulnerability of Outdoor Recreation to Increasing Heatwaves and Droughts

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ABSTRACT

Heatwaves can lead to extreme weather conditions, and droughts are becoming more common, lasting, and operationally significant, exposing outdoor recreation to these elements. This review summarizes existing data on the impacts of extreme heat and water shortages on recreation participation, safety, the experience quality, and management, and considers methods used to assess vulnerability. We incorporate results with an Exposure Sensitivity Adaptive Capacity well-constructed that interrelates hazards with outcomes in the form of heat strain in physiological processes, barriers to hydrologic access, distinct aggrade-water offenses, alteration of the ecosystem, and operational failures. Vulnerability is highly non-linear, so in all forms of recreation, increased risk due to heat is experienced to prevent thermal stress limits, and abrupt opportunity loss due to drought in the forms of streams flowing, the last stream flowing, and a regulation protection being above a specific threshold. Exertional heat stress and microclimate variability have a disproportionate effect on trial-based and endurance activities, and water-based recreation is limited due to low flows/levels and mediated by water-quality hazards associated with warming, e.g., harmful algal blooms. The emerging prominence of compound and cascading processes, such as the interaction of heat-drought and wildfire smoke, makes it rather challenging to attribute and predict such events, which are more likely to lead to closures and displacement. We approach this methodologically, suggesting that heatwaves and drought should be consistently defined, that heatwave and hydrologic definitions need to be applied more frequently in recreation-relevant exposure metrics, and that effective application of adaptation and equity indices requires rigorous estimation. We end up with integrated decision support priorities that convert the indicators into

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operational triggers and inclusive risk communication.

Keywords: Heatwaves; Drought; Outdoor Recreation; Vulnerability Assessment; Adaptive Capacity

1. Introduction

Most landscapes and economies are defined by outdoor recreation, which influences the health of the people, their cultural identity, and their local livelihoods in terms of hiking, camping, boating, angling, cycling, wildlife watching, and endurance events [1]. Outdoor recreation activities are generally concentrated during warm periods and destinations where the heat and access to water already limit ecological experience and human comfort. With the rise of intensity, duration, and frequency of extreme heat events and changes in the hydrologic regimes as climate change intensifies, outdoor recreation is becoming more exposed to hazards that have a direct impact on human safety and an indirect impact on the environmental qualities people pursue outdoors. Simultaneously, droughts are changing access to water-intensive recreation and increasing the risk of wildfire, and are resetting ecosystems upon which scenic, experiential, and biodiversity values depend, by drying the soil, soils, streams and lakes, and vegetation. The net effect is that outdoor recreation, which has always been a primarily discretionary sector of activity, is becoming increasingly acknowledged as climate-sensitive wellbeing and regional economy infrastructure, and thus an appropriate subject of systematic climate vulnerability assessment [2–4].

Extreme heat and drought affect outdoor recreation in a synergistic and complex way [5,6]. To begin with, heatwaves increase the likelihood of heat-related illness, particularly in processes involving a high level of effort and environments where there is not much shade, water, or a quick way to emergency services. The physiological risk increases nonlinearly as temperature, humidity, sun radiation, and exertion increase; that is, an identical air temperature might be very dangerous in one microclimate, terrain, and behavior, but very safe in another. Second, heat impacts the demand and experience of recreation: tourists can reduce the length of the visit, move to the morning or evening, or replace warmer destinations (e.g., higher altitudes, seashores), or skip outdoor recreation. Such behavioral reactions may lessen the exposure of other users and, at the same time, they can reassort pressure to a few more perceived secure or comfortable locations, which might increase crowding or trail erosion, or habitat disturbance. Third, drought also affects recreation by affecting physical accessibility and environmental quality: low reservoir levels may make boat ramps unusable, lower streamflow may reduce the opportunities of rafting and paddling, and warmer and stagnant waters may diminish water quality through harmful algal growth and proliferation of pathogens. Drought may also reduce vegetation and animal habitat and alter aesthetic and ecological qualities that drive recreation and, in certain instances, raise dust, reduce air quality, and increase the risk of being hit by falling branches or the death of trees in high-use areas.

Notably, heatwaves and drought are never common phenomena [7]. These have often been associated together as compound events, precipitation losses and soil moisture loss minimize evaporative cooling and increase surface temperatures, and long-term heat increases evapotranspiration and increases the severity of drought. This feedback causes seasons where thermal stress, water run shortage, and ecosystem susceptibility would also coincide. Coupling between drought and heat in most regions also increases the threat and possibility of prolonged smoke exposure, increasing the impact of wildfires with subsequent positive cascading effects on visitation, closures, and health. These compound and cascading risks confront traditional recreation management, which has been traditional in terms of seasonal planning and inert infrastructure as opposed to dynamically responding to the situation on the fly and in a highly dynamic environment. They also make research difficult, since observed changes in visitation and incidents of safety might be a result of overlapping drivers, heat, smoke, closures, and holiday demand, as opposed to a single climate variable [8].

Although the hazards have increased relevance, evidence regarding the effects of climatic changes on outdoor recreation is still disjointed across disciplines and is limited in geographic and methodological coverage [9,10]. Temperature-visitation relationships are frequently measured on an aggregate number basis and statistical demand modeling by studies in tourism economics, whereas thermal comfort indices and physiological thresholds are commonly the focus of studies in the field of public health and human biometeorology. The research of hydrology and ecology has provided information on the level of constraint in streamflow and dynamics in the temperature and quality of water and vegetation stress, yet not always related to the outcomes of recreation and management choices. Moreover, most recreation impact studies are done at the average seasonal conditions instead of the extremes, although extreme events may initiate thresholds leading to sudden closure, cancellation, or health emergencies. In the case of extremes, definitions of heatwave and drought are so diverse that it becomes difficult to compare across studies and synthesize at the meta-level. The heterogeneity of the methodological approach is not merely a scholarly aspect; it influences what information, which is relevant to the decision, can be obtained from the literature and then converted into the operational thresholds, warning systems, and adaptation strategies.

Another issue is that vulnerability is not homogeneous in terms of the type of recreation, locations, or people [11,12]. Trail activities (e.g., hiking, trail running, mountain biking) may involve a lot of metabolic heat generation and long-term exposure to solar radiation, especially when one is in Sun-free areas or in canyon areas where radiant heat loads are great. Recreation in water is frequently limited by hydrologic conditions: less than a certain minimum flow to safely boat or fish, excessive water temperatures to support some species, or other conditions of water quality that present human health hazards. Nature viewing and camping are sensitive to comfort, heat at night, fire regulations, and changes in the ecosystems, which will reduce the scenic value. The acute risk management needs of organized events and endurance races would include participant screening, on-site medical capacity, and heat safety, as well as the legal and reputational impact of the heat-related incidents happening. Under an evolving hazard regime, visitor access needs to be balanced by the protection areas and park agencies with regard to safety and conservation requirements [13]. Such patterns overlap with social vulnerability: older adults, children, individuals with chronic health issues, and outside workers (guides, rangers, concession staff), as well as visitors to whom cooling resources or transport options are not easily available, may have an increased risk or reduced options to substitution. There are also equity aspects when we consider an adaptation strategy, like a timed entry, a permit system, or raising fees, to decrease access to some people, or when a closure has a disproportionate impact on the communities that rely on seasonal visitation.

Because of these reasons, a vulnerability lens is becoming more and more needed in order to bring together climate hazards, exposure patterns, and adaptive capacity in a manner that is analytically sensible and practically implementable. Vulnerability often has flexible interconnections with both exposure (quantity, frequency, and duration of hazards to which a system is exposed) and sensitivity (the extent to which a system responds to hazards), and adaptive capacity (the potential to adjust, cope with, and anticipate hazard impacts) [14]. This framing would apply to what we call out-of-doors recreation by bridging the biophysical and behavioral aspects of risk. Not only does the exposure take part in capturing the incidence of heatwaves and droughts, but it also captures the microclimatic conditions that one experiences on a trail, at a campground, on open water, or even within a city park. Sensitivity includes the intensity of activities, dependence on water availability, remoteness, and rescue challenge, as well as ecological and aesthetic features that determine the quality of recreation. The adaptive capacity comprises the supply of shade and drinkable water, warning and communication, manageability and adaptability of the management policies as well as personnel, the availability of alternative locations, and the socioeconomic resources that help visitors and communities to adapt [15]. Notably, adaptive capacity is limited: even well-equipped facilities might have to be closed during extreme events of compounds, and options of substitution might also be limited when a large territory is broken by simultaneous heat, drought, and smoke.

Nevertheless, the task of transferring this conceptual framework into some quantifiable, comparable measurements is still a major obstacle. Measured on the hazard part, exposure to heat that is important in recreation is not entirely reflected by air temperature, and indices of Wet Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI) have included humidity, radiation, and wind to account more fully than air temperature does of the relevant physiological strain, but are not always employed in recreation research [16]. On the same note, drought has several dimensions, meteorological, agricultural, hydrological, and ecological, which have diverse recreation outcomes. An index based on the precipitation could follow the dryness in the region, yet fail to record the streamflow levels that dictate the rafting conditions or the elevation of the reservoirs that control the access of the boat ramps. On the outcome side, the number of visits and tourism revenue are easily accessible but not health risk in direct measure, and outcomes of health are seldom easily attributed to certain recreation settings. More recent data streams, e.g., anonymized mobility data, social media activity, and incident reports, are a promising direction but pose problems of representativeness, privacy, and interpretation. Besides, most research is only done on one park or within a small-time frame, making it difficult to generalize to other regions and climates.

This review summarizes the existing evidence on the effects of rising heatwaves and droughts on outdoor recreation and vulnerability according to activities, geographic location, and people. It is not just to summarize the documented impacts but also to assess the indicators, methods of analysis, and approaches to the concept that are most helpful in future studies and decision-making in parks, public lands, and the community that depends on recreation. We target specifically the extremes and thresholds, i.e., when we state that heat illness or mass trip cancellations, boating restrictions, or massive closures are driven, since these may become increasingly prevalent with climate warming and greater hydrologic variability. We also place a strong focus on compound and cascading risks because often the outcomes of recreation are an expression of many interacting hazards, and no single driver [17–19].

Based on this, this review is informed by four questions. The first one is by what mechanisms do heatwaves and drought impact recreation safety, demand, operations, and environmental quality, and how do these mechanisms vary among recreation types? Second, which data and indicators are typically employed to define the hazards of heat and drought in recreation research, and to what extent do they reflect site-specific exposure and thresholds of relevance to management? Third, which methodological tools have been used to measure vulnerability, i.e., statistical demand models, spatial vulnerability mapping, scenario-based projections, and mixed methods, and how strong or weak are they in terms of inferences and transferability? Fourth, how is adaptation worked out at visitor, site, and governance scales, what are the constraints or tradeoffs on adaptation, and how may equity-related considerations be integrated into the vulnerability evaluation and management reaction [20–23]?

The other part of the article is arranged in the following way. Section 2 explains how it will be reviewed and characterizes the evidence base with frequent data metabolite characteristics and frequent limitations. Section 3 provides a theoretical framework of pathways of vulnerability between heat and drought and recreation-related outcomes and contextualizes these pathways within an Exposure–Sensitivity–Adaptive Capacity scheme. Section 4 discusses the hazard and outcome indicators and summarizes the primary methods of analytical tools to measure vulnerability. Section 5 provides insight into the recreation type and area patterns of vulnerabilities, showing areas of hotspots and distribution. In Section 6, the adaptation options, limits, and research priorities are assessed based on areas of interest in decision-relevant thresholds and adaptation effectiveness. Section 7 also ends by providing a conclusion and a roadmap on how to produce more similar, equity-conscious, and operationally useful vulnerability assessments as heatwaves and droughts intensify.

2. Review Approach and Evidence Base

2.1. Review Design and Reporting Framework

The article meets the criteria of a structured narrative review design that aims to synthesize evidence among diverse disciplines that seldom use shared terms, outcome indicators, such as recreation and tourism studies, hydrology and water resources research, ecology and conservation science, human biometeorology, human health, and environmental management [9]. Due to the biophysical processes and human behavioral responses involved, we will take an open view to the study identification, screening, and synthesis, compatible with the existing systematic review conventions (e.g., Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-style reporting), but flexible enough to allow both qualitative evidence and case studies, and decision-support reports that are often central to applied recreation management. The general objective is to define the literature operationalization of heatwaves, droughts, the measurement of recreation outcomes, and vulnerability in terms of exposure, sensitivity, and adaptive capacity. Due to the fact that significant terms are inconsistently operationalized across the field, we normalize the key concepts and recreation-related nuances that have been applied across this review (**Table 1**).

Table 1. Core concepts and operational definitions used in this review.

Concept	Common Operational Definition(s)	Recreation-Relevant Nuance	Typical Data Source(s)
Heatwave	Absolute threshold (e.g., Tmax ≥ X °C for ≥2–3 days) or percentile-based (e.g., ≥90th/95th percentile for ≥2–3 days)	Risk depends on exertion, humidity, solar radiation, and nighttime recovery	Stations, reanalysis, gridded climate
Extreme heat exposure	Daily Tmax/Tmean; counts of hot days; warm-night frequency	Microclimate varies strongly by shade, elevation, aspect, riparian zones	Stations + downscaling; microclimate sensors
Heat stress (physiological)	WBGT, UTCI, Heat Index, Humidex	Better aligns with exertional risk and safety guidance than air temperature alone	Weather observations + modeled indices
Drought (meteorological)	Precipitation deficit; Standardized Precipitation Index (SPI)	May not reflect streamflow/access constraints	Precipitation records, reanalysis
Drought (hydrologic)	Low-flow frequency; streamflow percentiles; reservoir/lake levels	Directly determines boating/rafting/fishing opportunity and closures	Gauges, reservoir management data
Drought (ecological)	Soil moisture anomalies; vegetation stress indices	Alters scenic quality, habitat, dust, tree mortality hazards	Remote sensing, field monitoring
Compound event	Co-occurrence of heat + drought (often with smoke/air quality impacts)	Drives nonlinear outcomes: closures, health risk, displacement	Multi-hazard datasets

2.2. Search Strategy and Information Sources

The breadth of the relevant research is captured by compiling the searches of multidisciplinary bibliographic databases frequently used with the Science Citation Index (SCI)-indexed reviews, with occasional specific searches in health and environmental management sources to identify studies on heat-related illness, risk communication, and operational response. Search terms will be created to overlap climate hazards and recreation results with management settings. Key terms that can be used as hazards are heatwave, extreme heat, heat stress, thermal comfort, wet bulb globe temperature, UTCI, drought, water scarcity, low flow, water quality, whereas recreation-based terminologies are outdoor recreation, nature-based tourism, parks, protected areas, trail use, camping, boating, angling, rafting, visitation, and recreation demand. In an effort to capture the risk of compounds, extra combinations include wildfire, smoke, and air quality, as it is known that the drought-heat intersection is often operationally implemented through fire bans and smoke-related shutdowns. The search terms are translated according to database syntax, and results are limited to peer-reviewed sources where feasible, although very high-salient management evidence (e.g., agency technical reports describing heat closures, drought dispersal, or water access restrictions) can be selectively added when it reports information not covered in journal articles or when it describes operational criteria and decision-making rules [3,24].

2.3. Eligibility Criteria and Study Scope

Qualified researchers clearly connect the effects of heatwaves and/or drought to outdoor recreation, risks, and control measures. Outdoor recreation is also widely understood as activities that mainly take place in outdoor locations and are liable to ambient circumstances, including trail-based recreation, camping and nature viewing, water-based recreation, endurance activities, and recreation in conserved lands and urban/peri-urban green cover. Articles that concentrate on indoor recreation alone, or that investigate the effects of climate without any recreationally relevant findings, or whose conceptual discussions do not have an empirical or methodological basis, are considered out of scope. Due to the various ways in which drought impacts recreation, we also incorporate the work that examines hydrologic limits (e.g., streamflow minimums, reservoir maximums), ecological impacts (e.g., vegetation stress, habitat shift), and water quality risks (e.g., harmful algal blooms) when they have a direct relationship with recreation access, recreation experience, or health and safety. The studies, which focus on heat, are incorporated when they quantify or simulate participation in recreation, thermal comfort, heat stress, incident consequences, or management behaviors in recreation [20,25,26].

2.4. Screening, Study Classification, and Data Extraction

The screening is done in phases, which breaks down the relevance determination and intensive coding. The titles and abstracts will be evaluated at an early stage to ensure that a study deals with at least one of the focal hazards (extreme heat/heatwaves or drought) and one outcome that is recreation-related (use, experience quality, health/safety, operations, or economic effects) [18]. Full-texts are then assessed to ensure that the study operationalizes the hazard with the help of a specific measure and presents enough methodological details to make the results readable. To support the synthesis, included studies are categorized on a few analytic dimensions: the type of hazard being studied and its definition; the setting/type of the activity being studied and recreated; the outcome scale (behavioral, safety/health, operational disruptions, and ecological quality) the spatial and time scale of the analysis; the method used on the analysis (statistical modeling, spatial index mapping, scenario/projection analysis, qualitative or mixed methods, and decision-support/tool development) and the type of data utilized (climate observations, downscaled projections, visitation counts The well-organized code allows comparing cross-studies and maintaining valuable context, including possible causes of a result by temporary extremes, seasonal effects or long-term presence of drought.

2.5. Assessment of Methodological Quality and Inferential Strength

Due to the variety of study designs presented in the literature, the appraisal of quality is structured in terms of the strength of inferences and the validity of measurements, and not a single risk-of-bias tool [27]. To characterize the hazards, preference is placed on those studies which employ recreation-relevant metrics of exposure, clearly define heatwaves and droughts, and explain threshold selection with respect to physiological risk, access limitations, or management triggers. To determine the outcomes, the studies are assessed according to the characteristics of recreation measures being directly observed (e.g., counters, permits, ticketing) or indirectly observed (e.g., social media proxies) and the possibility of the health and safety outcomes being assigned to recreation contexts. To conduct statistical analyses, specific focus is given to confounding and attribution issues, which are typical of recreation demand studies, such as timing of holidays, school days, smoke incidents and holidays, closures, and macroeconomic issues. The studies that make use of proper controls, take advantage of quasi-experimental variation, or compare across sites and years are considered as yielding more evidence as compared to the studies that do it in a single site, short window analysis with little or no clear counterfactuals. In qualitative and mixed-methods research, credibility is determined by transparency in the selection of the sample, triangulation (e.g., operational data mixed with interviews), and the extent to which the findings can be converted into a decision-relevant constraints, thresholds, or adaptation measures.

2.6. Synthesis Approach and Integration across Disciplines

A narrative approach is used to synthesize evidence based on the Exposure Sensitivity Adaptive Capacity frame, which offers a common framework to combine biophysical hazards and human behavior and institutional response [28]. The synthesis continues with a linkage of hazard measures to domains of outcomes using direct pathways, which differentiate the direct heat stress hazards and indirect impacts, which are mediated by water scarcity, ecological transformation, or wildfire smoke. In cases where quantitative data are similar enough, findings are generalized in the form of directional effects and threshold behavior (e.g., non-linear drop in visitation after a certain heat index; loss of access at a particular elevation of the reservoir; safety incidents with high WBGT). Where comparability is constrained by definition or measure, synthesis focuses on methodological implications, finding out how evidence of the indicator selection or spatial scale or data constraints inform conclusions. In all types of evidence, review gives priority to decision relevance, which is the presence of actionable information in studies, including trigger points of advisories, criteria of dynamic closures or benefits, and tradeoffs of adaptation measures like shade infrastructure, water provisioning, and schedule shifts of organized events.

2.7. Characterizing the Evidence Base and Its Limitations

The resulting evidence base will be uneven and heterogeneous, which is due to the geography of data sources as well as the disciplinary silos in which recreation research is performed. Visitation and economic analysis are more likely to be located in those areas with well-established monitoring and high-profile areas of interest covered by protective measures, whereas exposure to microclimate and heat-health associations or equity-oriented analyses is relatively limited. Directly related drought research is often found in water-related settings in which access limits can be measured, but the effect of ecological droughts on scenic experience, wildlife observation, and long-term destination appeal is less commonly measured by recreation outcome metrics. Various subjects have the most enduring shortcoming of definitional inconsistency, as the terms heatwave and drought are operationalised differently in different studies, not always with explanations or sensitivity testing. The other repeat problem is the attribution of hazards in compounds since heat, drought, smoke, and management actions (restrictions or closures) may co-exist and interact to produce observed effects. Lastly, there is a high probability of publication and reporting biases, such as focusing on the most familiar destinations, underreporting of null effects, and the inadequate representation of populations and workers at the greatest risk of heat. Such constraints are prompting the focus later in the paper on standardizing indicators, enhancing the site-scale exposure measurement, and applying equity reasoning to the vulnerability measurement and adaptation evaluation [9,29].

3. Vulnerability Pathways and Conceptual Model

3.1. Outdoor Recreation as a Coupled Human–Environment System under Climate Extremes

The interplay of environmental conditions, infrastructure, institutional regulations, and human behavior influences outdoor recreation, thus outdoor recreation comprises a system of coupled human-environment where climate risks affect the ability to engage and the quality and safety of the experience [30]. Heatwaves and droughts impact recreation not just insofar as they relate to changing ambient conditions through the activity window, but also insofar as they relate to how the ecological and operational context in which recreation is accessed and enjoyed is altered. Such a connection is specifically decisive when there are extremes, and the consequences tend to change suddenly because of the physiological limits, safety measures, or the insufficiency of the infrastructure. Because of this, it is more correct to think of vulnerability as an emergent characteristic of a combination of hazard exposure and sensitivity and adaptive capacity amongst individuals, sites, and governance systems, and not as a direct implication of climate variables alone. We integrate the literature with an Exposure Sensitivity Adaptive Capacity framing linking heatwaves and droughts to recreation consequences via interacting mechanisms (**Figure 1**). **Figure 1** demonstrates that thresholds and responses of management mediate the occurrence of hazards as either health risks, loss of opportunity or displacement.

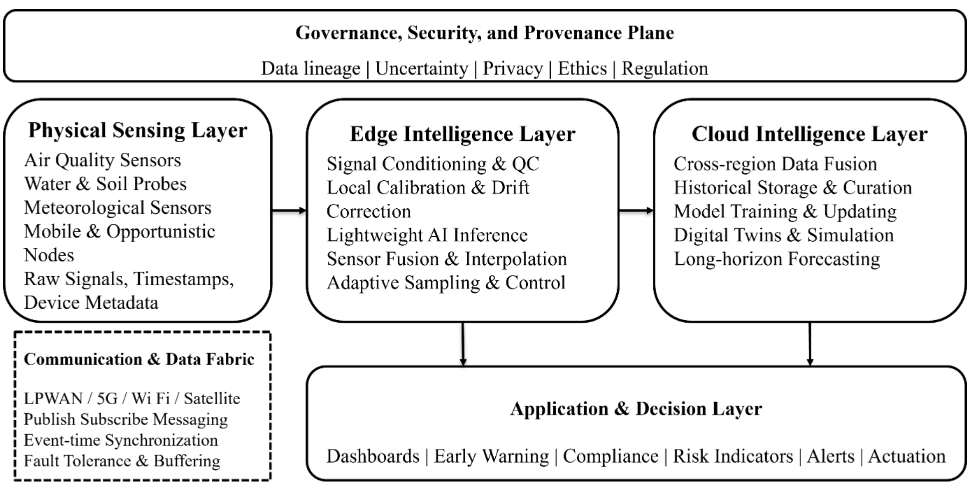

Figure 1. Conceptual model of outdoor recreation vulnerability to heatwaves and droughts.

3.2. Pathways Linking Heatwaves to Recreation Outcomes

Heatwaves pose direct health and safety hazards to outdoor recreationists, both through the strain of overheating on physical activity and through the risk of dehydration in a relatively shady environment, significant radiant load, and/or having less access to drinking water [31]. Humidity, wind, solar radiation, clothing, and exertion mediate the physiological effects, and this implies that integrated heat stress indices are commonly a superior predictor of extreme heat in recreation settings than air temperature. Avoidance and substitution are also effects of heat exposure on behavior and demand. Tourists can shorten travel time, change the time of the day to earlier or later, move to cooler microclimates (e.g., forested trails, riparian corridors, higher altitudes), or make replacements to indoor or water-based options. They may protect some people by reducing the direct exposure, but they may result in secondary pressures due to spatial and temporal displacement and focus use in a smaller group of perceived safe locations and produce crowding, resource effects, or increased conflict in locations that still have thermal refugia.

The heatwaves also impact recreation activities and risk management [10,32]. This is making agencies and organizers of events more dependent on heat advisories, hydration messages, staffing changes, and dynamic restrictions, and in certain situations, they either partially close down or close down altogether when the conditions cross specific thresholds or when the ability to respond to emergencies is constrained. The effects on operations have been a rise in demand for ranger and medical services, increased facility wear and tear, and reputational and liability issues of organized events and concessionaires. These dynamics of operations are the ones that belong to the vulnerability pathway since the availability or lack of an effective management response can turn a hazard into an experienceable stressor or an acute safety event.

3.3. Pathways Linking Drought to Recreation Outcomes

Drought has impacts on outdoor recreation by limiting hydrology, altering the ecology, and exerting a compounding impact on safety and access [20]. Drought-induced decreases in streamflow and reservoir levels may make water-based recreation sites unusable or unsafe, restrict the access of boats, narrow navigation, and constrain rafting, paddling, and angling in water-based recreation. Due to the fact that these effects often reach recognizable physical limits, drought may cause discontinuous opportunity losses even when more global climatic anomalies are seen as insignificant. Drought may also cause changes in the conditions of aquatic habitat, raising the temperatures of water and the dissolved oxygen levels, and therefore have an impact on the distribution and survival of fish, leading to management constraints on vulnerable species, which also directly limit angling and associated tourism [21].

The other route through which drought is connected to recreation vulnerability is water quality [33]. The low flows and high-water temperatures may elevate the chances of occurrence of harmful algae blooms and growth of the pathogen, especially in long-residence time lentic systems or in highly regulated systems where stratification and nutrient dynamics become more pronounced due to low inflow. These may result in swimming warnings, beach closures, and an increase in perceived risk, which retards visitation. Stresses on vegetation caused by drought, mortality of trees, and shifting patterns of wildlife behavior in terrestrial systems can modify scenic quality and chances of viewing iconic species, and this may decrease the experiential quality that determines nature-based tourism. Drought is also a source of dust and other particulate exposures and an aspect of poor air quality, even in the absence of smoke from wildfire, so that the visitors and workers can be uncomfortable and unhealthy. Operationally, drought may place pressure on infrastructure by limiting the availability of water at campgrounds, raising maintenance demands, and expanding the prohibitive measures on campfires or dispersed camping that alter the patterns of participation and visitor distribution.

3.4. Compound and Cascading Hazards: Linking Heat, Drought, Wildfire Smoke, and Secondary Effects

Heatwaves and drought are regularly closely interrelated, both physically and operationally, and their joint impacts are many times enhanced by other hazards that generate the domino effect [5]. Dry soils lead to a decrease in cooling by evaporation and raise the temperature near the surface, and contribute to the maintenance of heat extremes, whereas persistent heat raises the demand on evapotranspiration and exacerbates hydrologic drought. These interactions are capable of enhancing the likelihood of large wildfire occurrences, and in case such fires happen, smoke may exert significant health hazards and visibility impairments even in regions not near burn perimeters. In the case of outdoor recreation, smoke poses a significant inhalation risk that is potentially serious during exertion and can also initiate mass closures and cancellation of events. Compound events consequently generate profiles of multi-hazard exposures where recreationists experience related thermal overload, dehydration threat, and poor air quality, and managers must confront overlapping decision requirements of heat warnings, water limits, and smoke-related access restrictions.

Cascading can also be done via ecological and infrastructure channels. As an example, forests under stress due to drought are prone to outbreaks and mortality by pests, and this adds additional risk to falling trees and may also change the ability of trails to be hazardous and need less maintenance [34]. In the water environment, low-flow conditions could be combined with warmer water temperatures and concentrated pollutants to push systems beyond water-quality standards that would necessitate advisories or state shutdowns [35]. These cascading processes highlight the importance of vulnerability analyses that consider heat or drought separately in understanding risk in the situation under which it is operationally most relevant, i.e., the extreme conditions of two or more constraints coming together.

3.5. Exposure–Sensitivity–Adaptive Capacity (ESAC) as an Organizing Framework

To incorporate these pathways into a conceptually consistent model, this review uses the ESAC framework. Exposure refers to the intensity, frequency, duration, and timing of heatwaves and droughts external to the recreation system. Sensitivity describes the inherent degree to which a system responds when exposed—determined by activity type, physiological status, infrastructure design, and ecological dependencies. Adaptive capacity refers to the resources, options, and flexibility available before or during a hazard event to anticipate, cope with, or adjust to impacts [36,37].

Critically, adaptive capacity must be operationalized distinctly across scales. Visitor adaptive capacity includes schedule flexibility, financial resources for substitution, protective equipment access, and heat-health literacy. Manager adaptive capacity encompasses staffing, forecasting systems, dynamic closure authority, communication infrastructure, and investment budgets. Community adaptive capacity involves economic diversification, inter-agency coordination, social networks, and equitable service distribution [38].

Adaptive capacity refers to the capacity of recreationists, managers, and communities to respond to hazards and adapt to them in advance [14,39]. To visitors, adaptive capacity will also encompass risk and protective behavior knowledge, availability of cooling and hydration, flexibility of schedule, the ability to substitute plans or buy equipment, and financial means to change plans or buy equipment. To the managers, it will encompass capacity, staff, and medical preparedness monitoring and forecasting, flexible permitting and closure policies, communication systems, and the capacity to invest in heat and drought-resilient infrastructure. Adaptive capacity to changing conditions related to the way products are offered in a season, business flexibility, and collaboration with land management agencies is considered the adaptive capacity of the gateway communities and tourism operators. Importantly, adaptive capacity can be limited by social injustices, institutional requirements, and environmental constraints, i.e., adaptation can lessen but not eradicate vulnerability by growing extremities.

3.6. Threshold Behavior and the Nonlinearity of Recreation Vulnerability

Threshold behavior is a characteristic of the vulnerability to heatwaves and droughts [40]. Most effects do not go in proportion with incremental warming or drying, but they arise when conditions pass physiological, infrastructural, or regulatory limits. Heat-health hazards may soar above certain temperature, humidity and workload combinations; water prospects can fail as a result of decreases in the water level of the reservoirs beneath the level of ramp usability or stream flow within the equilibrium between the cut-offs on navigability or ecological preservation; and visitation may rise or fall abruptly as the agencies initiate closures or as smoke makes the outdoors pursuits unsafe. These thresholds make demand and safety results nonlinear and may cause sudden economic effects to those communities whose livelihoods rely on peak-season tourism. The identification of threshold behavior is consequently critical to research synthesis and relevance in management since it presupposes the conditions that average-condition analysis might miss when the greatest likely losses are experienced.

3.7. Equity and Distributional Dimensions of Vulnerability within the Conceptual Model

Vulnerability is not uniform, and the ESAC framework gives an option to model the distribution between users and workers. Exposure is potentially greater because recreation may occur on peak heat days because of work schedules or lack of flexibility, and recreation workers may spend extended time outdoors as part of the support services. Old people, people with chronic illnesses, children, and those with limited experience of acclimatization or access to protective equipment should have a high level of sensitivity. Adaptive capacity is usually varied according to income, language, availability of transport, and knowledge of local conditions and warning systems. Protective though they are in the aggregate, management responses can create new inequities as access is differentially reduced by closures, permit systems, or fee increases, or adaptation investments favor high-profile destinations over important places locally. The equity factor in the conceptual model should also mean an effort to incorporate hazard exposure as well as social and institutional factors in the determination of coping alternatives, as well as the distribution of benefits and adverse effects of adaptation responses [32,41].

3.8. Implications of the Conceptual Model for Assessment and Decision Support

The conceptual model that will be formed in this way is that the vulnerability assessment must link recreation-relevant measures of hazards to outcome measures via unambiguous lines and must include compound hazards, thresholds, and adaptive capacity at as many levels as possible [42]. It also suggests that effective appraisals should be scale-sensitive: visitor experience and heat stress are usually two variables in which a microclimate and route dynamics factor, but drought limits may come to rely upon watershed-based hydrology and road design urbanism. To support decision-making, the model recommends that the actionable products are those that can convert hazards into operation triggers and operational interventions, including the identification of thermal refugia in parks, determination of reservoir or flow levels to reliably predict the loss of access, and the incorporation of the heat, drought and smoke in unified advisories. These implications drive the synthesis of indicators and methods in Section 4, in which we consider the measures of exposure, sensitivity, and adaptive capacity offered by the literature and the performance of the various methods upon the compound, threshold-driven process in which we investigate recreation risk, which determines outcomes with increasing heatwaves and droughts.

4. Indicators and Methods to Assess Vulnerability

4.1. Rationale for Indicator Selection in Recreation Vulnerability Assessment

To measure vulnerability in outdoor recreation, there is a need to have indicators that can be both climatologically defensible and interpretable at scales pertinent to the recreation setting, as well as directly related to outcomes that are important to recreation safety, access, experience quality, and operations. The literature is broad in terms of methods, with straightforward temperature and precipitation anomalies, and combined heat stress indexes and hydrologic limits. Such diversity is a representation of actual differences in data availability and disciplinary practice, but results in comparability problems. Vulnerability of recreation assessment can be most informative, whereby a rationale is provided why a particular hazard indicator is relevant to the physiological and operating processes outlined in Section 3, and where the spatial and temporal scale of the indicator is adjusted to the scale at which visitors perceive conditions and managers make decisions [22].

4.2. Heat Indicators and Recreation-Relevant Exposure Characterization

Near-surface air temperatures are used to reflect heat exposure in many studies as mean temperature, daily maximum temperature, or the number of days when the temperature is above a given threshold. These measures exist on a large scale and spread over time and space, and hence allow general comparisons and trend analysis. Nevertheless, air temperature may not be a strong proxy of heat strain on physiology in outdoor recreation, in which exertion, solar radiation, humidity, and wind are essential factors dictating heat strain. As a result, a growing number of the literature uses composite indices that have a closer approximation of human thermal load. They have Heat Index and Humidex, which use humidity, and Wet Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI), which are designed to be representative of heat stress either with multiple meteorological drivers in occupational and sport safety or with one meteorological driver in biometeorology [43,44].

The characterization of heatwaves creates further methodological heterogeneity because the characterization of heatwaves takes different thresholds, baselines, and duration requirements [45]. Definitions can be absolute, e.g., above a given temperature, percentile-based, e.g., above the 90%, 95% German temperature history, or impact-based, e.g., above WBGT levels associated with safety hazards. Time and constancy are significant in recreation since there are consecutive hot days which may decrease nighttime refreshment, enhance the probability of dehydration, and max out cumulative strain of a multi-day journey or occasion. The temperatures of nights, e.g., minimum temperature deviations or warm nights occurrence, are especially applicable to camping as well as the recovery of staff and visitors. Besides that, recreation exposure is highly influenced by diurnal timing and microclimate. Localized thermal refugia/hotspots. Latent factors: Canopy cover, closeness to water, slope aspect, and height imply that coarse climate grids can be misleading about the conditions that can be experienced on the trail or at an open water location. Research involving site-scale measures of microclimate, or model-based downscaling to capture shade and terrain, can thus substantially better estimate exposure parameters of decision importance, but is less widespread because of data and modeling requirements.

4.3. Drought Indicators, Hydrologic Thresholds, and Water-Quality Proxies

Drought is not a one-dimensional condition, and indicators applied in recreation studies are dependent on the route by which drought has an impact on recreation [21]. Meteorological drought is commonly modeled by precipitation shortages or standardized indices like the Standardized Precipitation Index (SPI), which is a probabilistic index of dryness at a particular accumulation period. With a central role of evaporative demand (especially in warming), a temperature or potential evapotranspiration-based index, e.g., Standardized Precipitation Evapotranspiration Index (SPEI), can indicate the combined effect of decreased precipitation and increased water demand in the atmosphere. Agricultural and ecological drought are commonly modeled by soil moisture abnormalities or remotely sensed vegetation indices to record the plant stress and productivity alterations that can be pertinent to scenic worth, wildlife habitat, and dust production.

In water-based recreation, as well as in numerous management decisions, hydrologic drought indicators may be far more directly applicable than the meteorological indices. Operational constraints that can be linked to streamflow percentiles, low flow frequency, the elevation of the reservoirs, the level of lakes, and the state of groundwater include navigability, the capability of the boat ramps, and the minimum flow limits that ensure the safety or ecological protection. The indicators allow characterization of opportunity loss, threshold-based, such that the recreation availability shifts suddenly after a physical or regulatory threshold is passed. The water quality is becoming increasingly understood as a significant reconciler in the outcomes of drought and recreation. Whereas the spatial density required to monitor water quality is not always as dense as recreational sites may require, other studies have utilized proxies or correlated indicators of water quality, including water temperature, residence time, nutrient loading setting, or the previous occurrence of harmful algal blooms to estimate the potential threat of harmful algal blooms or pathogen risk. The best tests combine hydrologic indices and measured water quality information, as it is understood that water scarcity is not always a recreation-relevant outcome, but the related access and health limitation [20,46].

4.4. Outcome Indicators: Measuring Recreation Impacts and Vulnerability Endpoints

Recreation vulnerability assessments are based on outcome indicators that describe both behavioral change and risk outcome [22]. Visitation and use measures are usually based on permit data, ticketing, trail and vehicle counts, records of campground occupancy, and in a few instances on compiled datasets of mobile movements. These measures aid in the analysis of the response to heat or drought in the use, as well as substitution among sites. In studies that focus on tourism, economic impacts are commonly estimated based on revenue, lodging and occupancy, concession sales, or based on a modeled visitor spending multiplier. Health and safety outcomes are less regularly reported but may involve search and rescue incidents, emergency care response, reports of heat illness, and, in a few cases, health surveillance data that are related to place and time. The proxies used in the case of environmental and experience endpoints are the condition of vegetation, the temperature of the stream, the presence of wildlife, visibility, and qualitative visitor satisfaction or perceived comfort based on surveys.

There are significant interpretive implications to the selection of outcomes. Reduction in visitation in hot seasons either may be attributed to less exposure and consequently a protective behaviour response, but may also signify missed access and economic damage among recreationally reliant communities. Equally, constant visitation during hot weather might signify strength in individual users but might conceal the potential danger in less-prepared categories. Due to this fact, vulnerability research is now more focused on multiple outcome domains, both participation and safety endpoints, and on distributional patterns instead of aggregate averages [47,48]. **Table 2** summarizes the key indicator families of hazard and the recreation endpoints that they serve.

Table 2. Indicator families used to characterize heat and drought hazards and the recreation endpoints they inform.

Domain	Indicator Examples	What It Captures	Primary Recreation Outcomes It Links to
Heat hazard	Tmax anomalies; hot-day counts; warm-night frequency	Frequency/intensity/timing of heat extremes	Visitation timing/volume; camping comfort; incidents
Heat stress	WBGT; UTCI; Heat Index/Humidex	Physiological strain incorporating humidity/radiation/wind	Heat illness risk; event safety decisions; search and rescue (SAR) demand
Drought (meteorological)	SPI/SPEI	Dryness over specified timescales	Broad demand shifts; vegetation stress context
Drought (hydrologic)	Streamflow percentiles; lake/reservoir elevation	Access/navigability constraints	Boating/rafting viability; ramp usability; restrictions
Water quality	Water temperature; bloom advisories; pathogen indicators/proxies	Health risk and perceived safety	Swimming closures; shoreline visitation; angling impacts
Ecosystem condition	Normalized Difference Vegetation Index (NDVI)/vegetation stress; tree mortality; habitat indicators	Experience quality and safety hazards	Scenic value; wildlife viewing; campground safety
Operational status	Closures/restrictions; fire bans; advisories	Management mediation of hazard impacts	Attendance, displacement, compliance, economic losses
Human response	Mobility data; surveys; route choice; time-of-day shifts	Behavioral adaptation/substitution	Displacement pressure; crowding; equity patterns

4.5. Statistical and Econometric Approaches to Quantify Climate–Recreation Relationships

A large part of the literature employs statistical models to approximate the relationship between climate variables and recreation demand or visitation [49,50]. The most typical methods are regression models with daily or monthly visitation dependent on temperature, precipitation, and drought statistics, often with controls for day-of-week, seasonality, holidays, and site-specific fixed effects. Such nonlinearities as steep declines in visitation beyond comfort limits, and heterogeneity among user groups or between sites (where such data are supplied) can be detected by these models. The exploitation of time variation and across sites is commonly done using panel data techniques to enhance generalizability in the analysis of single sites. Also, the nonlinearity in Section 3 would be represented with threshold models and spline-based specifications, as the user would undergo sharp transitions when conditions are too hot, and access would be limited by hydrologic thresholds.

The inferential power of such strategies is largely determined by the way of dealing with confounding and co-occurring hazards. The heat can be extreme and be accompanied by wildfire smoke, restrictions, and closures, and drought stages can cause management action to be implemented, which may have a direct impact on visitation. Unless explicit representation of these overlapping drivers is done, there can be a biased estimation of climate effects. Enhanced designs thus include smoke and air quality indicators, closure variables, and interaction terms, which represent the conditions of the compounds. In situations where possible, quasi-experimental designs that take advantage of sudden policy instigators or geographical boundaries of exposure may enhance attribution and are less frequent.

4.6. Spatial Vulnerability Mapping and Index-Based Assessments

Spatial methods transform the concept of vulnerability into geographic products that may be used to plan and allocate resources. In many studies, composite indices are constructed consisting of exposure to hazards (e.g., increasing rates of hot days, frequency of drought) with indicators of sensitivity (e.g., intensity of activity, distance, lack of shade or water, reliance on water access infrastructure) and adaptive capacity (e.g., availability of cooling facilities, information availability, management resources, proximity to substitutes)[36]. Multi-criteria techniques are generated based on GIS to produce vulnerability surfaces or hotspot maps over parks, trail networks, watersheds, or recreation areas. This kind of mapping may identify groups of high exposure and overlap with high-use assets and little adaptive capacity that are useful in prioritizing interventions.

The key methodological issues in index-based mapping are weighting decisions, indicator multiplicity, and the fact that proxy proxies mapped may not be consistent with processes. Numerous indices are based on easily accessible datasets, which are not likely to reflect microclimate refugia, local water access limitations, or real-time operational abilities. Credibility is reinforced by transparent weighting methods, sensitivity analyses, and comparison with observed results (e.g., closures or patterns of incidences). Spatial measurements are also moving to more actively consider accessibility and substitution, noting that vulnerability is also constructed by visitors being able to move to other locations within a travel time acceptable to them, and the substitutes are also at risk in the same exposure to heatwaves at regional scales. Since the objectives of estimating the sensitivity of visitation to real-time closures methods vary due to the diversity of objectives, it is necessary to use inferential strength and operational usefulness (**Table 3**)[51].

Table 3. Major methodological approaches for assessing recreation vulnerability to heatwaves and droughts.

Approach	Typical Inputs	Outputs	Strengths	Key Limitations	Best Used for
Statistical/econometric demand models	Climate + visitation/time controls	Climate–use relationships; thresholds	Quantifies behavioral response; scalable across years	Confounding (smoke/closures/holidays); limited site mechanism detail	Estimating visitation sensitivity; forecasting demand changes
Spatial index mapping (Geographic Information System, GIS)	Hazards + recreation assets + capacity proxies	Vulnerability hotspots	Actionable prioritization; visual communication	Weighting subjectivity; proxy validity; microclimate often missing	Planning investments; identifying high-risk nodes
Scenario/projection studies	Downscaled climate + exposure–outcome models	Future exceedance/impact ranges	Forward-looking planning under uncertainty	Assumes stationarity of behavior/adaptation; model spread	Long-term strategy; season-shift planning
Mixed methods (surveys/interviews + data)	Visitor/manager insights + quantitative indicators	Mechanisms, barriers, acceptability	Reveals constraints and real-world decision rules	Generalizability may be limited	Designing interventions; equity and feasibility assessment
Decision-support tools (dashboards/triggers)	Real-time monitoring + thresholds	Alerts, operational triggers	Direct operational relevance	Requires maintenance, governance alignment, evaluation	Real-time management; integrated advisories

4.7. Scenario, Projection, and Climate Analog Approaches

Futures vulnerability would be determined by comparing the results of the recreation with the future predictions of the hazards[10,12]. Scenario-based research involves downscaled climate projections to approximate the changes in the frequency and intensity of heat extremes and drought conditions, and then transforms these changes into forecasted changes in visitation, opportunity loss, or safety risk. Methods include statistical extrapolation based on historical climate-visitation relationships through mechanistic models based on physiological thresholds or hydrologic limits. Climate analog uses projected conditions in a specific location to compare them to existing conditions in warmer or drier areas to draw an intuitive conclusion on how this area might behave or operate, which is often approached intuitively by managers, this approach must not ignore the potential differences in context, such as infrastructure, visitor composition, and governance. Uncertainty in projection studies is also a key factor due to the spread of the model, choice of downscaling, and emission scenarios, as well as the likelihood of behavioral reaction or adaptation to change over time. Most decision-relevant analyses thus take the form of ranged outcomes and focus on the probability of threshold exceedance as opposed to individual deterministic predictions.

4.8. Mixed Methods, Qualitative Evidence, and Decision-Support Tool Development

Qualitative and mixed-methods research is important as it helps to provide crucial evidence since the recreation vulnerability is framed by perceptions, preferences, and institutional constraints that cannot be easily observed in quantitative datasets [52]. The perception of risks, readiness to change time or destination, and the acceptability of management intervention, like timed entry or dynamic closures, are recorded in visitor surveys and interviews. The interviews with the managers and case studies shed some light on the ways in which heat and drought are operationalized in practice in terms of their advisories, staffing, modifications in infrastructure, and communication with the public health and water agencies. Such studies tend to provide adaptation barriers, such as insufficient budgets, incompatible mandates, communication barriers, and equity issues. Triangulation with qualitative data. Mixed-method designs can be used to link perceived risk and management decisions to quantifiable outcomes by using visitation or incident data to triangulate qualitative results.

Decision-support tools constitute a new frontier of application, and they have integrated monitoring and forecasts as part of the operating triggers [53]. They could be heating alert systems that are park-specific, dashboards that integrate heat stress indices with the visitation predictions, and drought-stage frameworks that specify the limitations depending on the reservoir level, flow or water quality measure. Such tools must be useful in that they can be used to convert complex hazard information into actionable guidance, articulate uncertainty, and be consistent with agency capacity and legal requirements.

4.9. Cross-Cutting Methodological Issues and Best-Practice Considerations

Throughout the approaches, three problems are repeated. To begin with, the choice of indicators has a strong influence on the conclusion, especially where the studies use air temperature or precipitation as the sole indicator instead of indices that show physiological heat strain and hydrologic access thresholds. Second, scale alignment is critical: local vulnerability can also be heavily dependent on localized microclimate and infrastructural limits, and most datasets are regional and can blur the limits that are extreme, leading to closures or cases of morbidity. Third, the attribution of hazards of compounds is critically needed in a warming climate, where heat, drought and smoke are more and more co-occurring, and management interventions act in mediation between observed results. These problems indicate that strong vulnerability tests must combine various hazard signatures, express thresholds, encompass management actions as a section of the causal pathway, and harmonize modeled patterns of vulnerability with observed closures, incident statistics and behavioral relocation. Equity-forward assessment is also based on such improvements as they would allow assessing who is exposed, who could adapt, and how recreation benefits and burdens would be distributed among recreation users, workers and communities [54].

5. Vulnerability Patterns across Recreation Types and Regions

5.1. Interpreting Vulnerability Patterns across Diverse Recreation Systems

The relationship among activity-specific exposure profile, the extent of reliance on water and thermal comfort, and the capacity to change behavior or operations of visitors and managers results in patterns of vulnerability to heatwaves and droughts [55]. Since outdoor recreation is not an isolated industry, but instead a collection of diversified risk profiles, each with unique physiological needs and infrastructure constraints, vulnerability is better understood as a differentiated risk profile as opposed to a consistent reaction to warming and drying. The identical heatwave can put health at risk for high-exertion trail users, limit the participation of families seeking comfort-based experiences, and change the demand to water bodies that become simultaneously less safe or less available in case of drought. Similarly, a drought episode can have a small impact on some terrestrial activities in the short-term and drastically limit water-based opportunities with hydrologic thresholds and water quality loss. This part is a synthesis of the prevalent patterns of vulnerability that are apparent in the literature, categorized by recreation type and then placed in the regional contexts where exposure and adaptive capacity vary systematically.

5.2. Trail-Based Recreation: Exertional Heat Risk, Microclimate Dependence, and Displacement Effects

Hiking, trail running, and mountain biking, which involve trail-based activities, are often very sensitive to heat due to the combination of metabolic heat generation and ambient thermal loads, which increases the risk of heat strain during prolonged effort. The most vulnerable are those with low amounts of shade, high amounts of radiant load, and scanty amounts of water, such as open desert trails, exposed ridgelines, and canyon systems with inadequate airflow. Such circumstances may cause nonlinearities in risk, which are sharp, where minor rises in temperature or humidity can cause perceived and physiological strain to exceed tolerable limits. To this, users have evolved by changing the time of activity to the early morning and evening hours or choosing routes where there is a canopy cover, riparian shade, or greater height. This behavioral adjustment may also minimize the exposure and exposure of individuals, but may also cause crowding pressure to be concentrated on a smaller range of "thermal refugia" that may accelerate trail wear, erosion, and conflict in places of high accessibility [56,57].

The remote and rescue logistics are also factors that further influence the vulnerability to trail users. The distance to trailheads, low cell signal coverage, and challenging topography can easily convert mild heat stress to a critical one in case of dehydration or heat illness and there is no rapid aid. These are also some of the factors that affect the management responses, where agencies can either issue a closure, change staffing, or increase risk communication in extreme situations during extreme heat periods in remote areas. According to the literature, the sensitivity modifiers that make vulnerable assessments of trail-based recreation most informative are those that include the concept of microclimate heterogeneity and route difficulty, and accessibility to water and shade, as opposed to reliance on coarse temperature deviations [58].

5.3. Camping and Nature Viewing: Comfort Thresholds, Nighttime Heat, and Drought-Driven Ecosystem Change

Camping, picnicking, and nature viewing may be positioned as less physically taxing than trail-based recreation, but their susceptibility can be significant since comfort is one of the main factors of participation and enjoyment [29,59]. Discomfort and loss of sleep can decrease demand due to heatwave, especially when the nights are hot and cannot allow the body to rest properly. This type of pathway is particularly applicable to camping, in which the lack of cooling within the home encourages exposure to hot nights and in which the appeal of the lengthy journeys is dictated by the potential to rest pleasurably. Operation conditions as well as the infrastructures related to heat in campgrounds and day-use areas, include augmenting water demand, pressuring of onsite water resources and aggravation of the need for shaded structures and cooling shelters.

Drought conditions predispose these activities over the long-term ecological and aesthetic channels [60]. Stress on vegetation, a shift in phenology, lack of water in riparian corridors, and alteration of wildlife distribution can reduce scenic value and perceived quality of nature, which may have a long-term of effect than that of event-oriented studies. Direct safety hazards in campgrounds and access roads can also arise due to drought, causing trees to die, adding more to the maintenance-heavy workload and sometimes even requiring closure or redesign of a site. These avenues highlight the fact that vulnerability to comfort- and experience-based recreation can be manifested by shifts both in destination desirability and satisfaction and seasonality as well as instantaneous safety incidences.

5.4. Water-Based Recreation: Hydrologic Thresholds, Access Loss, and Water-Quality Mediated Risk

Water-based recreation, such as boating, paddling, rafting, angling, and swimming, can often prove to have the most apparent threshold-based vulnerability to drought since the activity requires minimum water levels, flows, and quality conditions to be met. The height of reservoirs and the level of lakes have direct impacts on the usability of the boat ramps and the level of accessibility to the near shore, and the stream flow limits influence navigability, safety, and the viability of commercial activity like guided rafting. Low flows also initiate ecological protection in most systems, such as angling restrictions or water reductions, which also limit recreation. The dynamics have the potential to cause sudden losses of opportunities when there are drought episodes despite larger meteorological signals, which only indicate moderate dryness [20,61].

Drought and heat waves both contribute to water-based recreation using water temperature and quality routeways [62]. Warm water and longer residence times may elevate the chances of dangerous algal spikes and pathogen dangers that may result in advisories and closures that have a direct impact on swimming and use of the shoreline. In the case of angling, water becoming hot and having minimal dissolved oxygen may change fish behavior and survival, lower the catch rate, and cause restrictions to protect fish. These pathways may interrelate with behavioral substitution in complicated ways. The heatwave could lead to more water access due to an increase in accessing water in order to cool down; however, environmental factors causing the high demand may also cause poorer water quality and growth of risk factors. Water-based vulnerability assessment is thus enhanced by the use of hydrologic and water quality indicators along with visitation patterns, where less opportunity occurs due to access limitations and less participation occurs due to perceived or communicated health risk.

5.5. Organized Events and Endurance Recreation: Acute Risk Governance and Scheduling Sensitivity

Organized endurance events and adventure recreation are a unique vulnerability profile since individuals are involved in a concentration of people in large numbers at specific times, with or without extreme effort, over a period of time [19,63]. The activities are increased in risk by heatwaves due to physiological strain, as well as drought and smoke, which can influence the quality of air and safety in operations. The sufficiency of heat safety measures, medical preparedness, route planning, and schedule or distance adjustment are the factors that predetermine vulnerability. Contrary to dispersed recreation, where a single person can substitute, an event must be made out of a collective decision and be liable and face reputational risks in case of an occurrence of an extreme situation, which may result in illness or death. Consequently, event managers and authorities putting on such events are moving to more and more threshold-based requirements and decision-making guidelines, like WBGT triggers to change or cancel. The evidence is further indicative that the availability of the adaptation options is not evenly distributed among the organizations, with the resource-rich events being more able to offer cooling stations, medical staffing, and communication systems, and the smaller events being more vulnerable to operational failure in hot environments.

5.6. Protected Areas and Park Operations: Dynamic Closures, Infrastructure Stress, and Mission Tradeoffs

During heatwaves and droughts, the protected areas are centers of recreation facilities, ecological quality, and public safety and, accordingly, are vulnerable centers of risk [64]. The vulnerability of operations is manifested in the higher number of people required in times of extreme situations, extended search-and-rescue requirements, and the difficulties posed by heat and water shortages to maintain the operations. Heatwaves may overload roads and facilities, raise water demands at visitor centers and campgrounds, and compel agencies to invest limited resources in risk communications and responding to emergencies. Drought worsens infrastructure limitations as it reduces water availability and the necessity to restrict such activities as campfires, dispersed camping, and other activities associated with fire hazards. In extreme circumstances of compound conditions, the closures will increase, and this brings issues of equity in access and how the economic impacts are shared with the gateway communities.

These dynamics bring out mission tradeoffs that come out in the middle of the safeguarded regions. Agencies should find a tradeoff between the openness to the public and safety requirements and biodiversity conservation, especially when drought stress causes the ecosystem to be vulnerable to trampling, disturbance by wildlife and invading species. The management actions themselves figure in the vulnerability pathway since timeliness and extent of restrictions can decrease the risk or in case of improper communication, they redirect the visitors to less prepared sites or induce risky behavior. Therefore, the vulnerability of the protected areas cannot be ascribed to the exposure to hazards only, but also to the institutional capacity, flexibility of its governance, and real-time monitoring and decision support [65,66].

5.7. Regional Hotspots and Context Dependence in Exposure and Adaptive Capacity

The vulnerability of recreation is highly conditioned by the regional conditions since the identical strength of hazards may lead to various results based on the existing climate, infrastructure, and opportunities to replace them. The high baseline exposure to heat and enduring water scarcity in arid and semi-arid areas, as well as drought events that result in rapid decreases in surface water availability and an increased risk of wildfire, are frequent occurrences. Low thermal refugia, longer distances of travel, and less-developed water infrastructure often contribute to vulnerability in such settings, and adaptive capacity is reliant upon specific investments in shade, water provisioning, and communication [67].

The regions with Mediterranean climate, as well as other areas with dry summers, may have a strong interaction between heatwaves in summer, the persistence of droughts, and the smoke of wildfires [68]. In this case, the risk profile of compounds often leads to closures and cancellations, and vulnerability analysis should reflect the exposure to smoke as a parallel limitation, but not a random outlier. The situation is different in mountain areas: high-altitude areas can provide thermal refugia that draw displaced demand during heatwaves, yet drought can decrease streamflow and worsen riparian conditions, and access can be limited by limited infrastructure and rescue capacity. Another context is taken up by urban and peri-urban parks, where the urban heat island both exposes more, but the parks also become even more significant cooling havens. Vulnerability overlaps with social determinants in such settings, such as disparities in accessing transportation, home cooling, and information.

In some areas, the substitution alternatives may mitigate or increase vulnerability. With other places being available and varying in accessibility, visitors could relocate to cooler or drier locations and redistribute economic gains and environmental strains. Where hazards are regionally coordinated, as is typical during large heat domes or multi-year droughts, substitution becomes less viable, and vulnerability may increase exponentially since all the available destinations are limited at the same time.

5.8. Equity and Distributional Vulnerability across Users, Workers, and Communities

Distributional vulnerability is a cross-pattern that is observed in reconstruction types and regions. The exposure usually increases among workers who staff recreation areas, such as guides, concession employees, rangers, and maintenance crews, since their outdoor time is not as discretionary and lengthy. Tourists who have few schedule options might not be able to evade hot seasons, and those who have fewer resources might be hindered by not being able to afford protective equipment, visiting fewer hot alternatives, or changing their plans. The sensitivity varies with the health status and acclimatization and older people, children, and those with chronic diseases are at a greater risk in heatwaves. The effectiveness of warning communication depends on language access and knowledge of local hazards, so that adaptive capacity is shaped differently than it is often directly measured in the recreation literature [69].

There is also unequal vulnerability at the community level [70]. Economies that are heavily reliant on recreation and struggled to maintain normal levels of operation during closures or extreme conditions, gateway towns are prone to disproportionate losses and hardship related to emergency services, and pressure on infrastructure as more people require emergency services. The strategies aimed at adaptation to decrease risk may generate new inequities when based on heavy use of permits, prices, or capacity restrictions to decrease access by low-income users or when investments are made in flagship destinations at the cost of local parks that are used as daily recreation and cooling areas. The existence of such patterns supports the importance of vulnerability assessments that do not rely solely on aggregate visitation response but rather on distribution of exposure and coping choices, and expressively upon how management activities affect the beneficiary of adaptation and residual risk the victim.

The trends that are summarized in this section indicate that the most vulnerable situations are those where high exposure is associated with high sensitivity and limited adaptive capacity, especially in the case of events like compound events that interact between heat, drought and smoke[71]. Trail and endurance recreation are highly sensitive with physiological mechanisms and distance limitation, whereas water-based recreation has high opportunity loss with a threshold and water-quality mediated risk. Both immediate heat stress (warm nights, in particular) and longer-term changes in the ecosystem due to drought, which may change the desirability of the destination, are hazardous to comfort-oriented activities like camping and nature viewing. In all categories, the role of the protected areas and the park agencies is to be a key mediator between hazards and operational response that may cause risk reduction or redistribution.

These lessons drive two priorities on the assessment strategies discussed in Section 4[3]. First, vulnerability indices must be specific to the prevailing pathways of each type of recreation, by focusing on microclimate and exertional heat stress (recreation of trails and endurance) and hydrologic and water quality limit (water-based recreation). Second, the substitution and displacement should be given a face at the regional scales, and this should be explicit because it has been found out that adaptation via behavior change can shift risk spatially and socially and not actually. This framing also guides the synthesis of adaptation in Section 6, where interventions are estimated based not only on their ability to lower average risk but also on their impacts in the extremes of compounds, as well as its equity implications to users, workers, and communities.

6. Adaptation, Management Implications, and Research Priorities

6.1. Adaptation as Risk Reduction in a Threshold-Driven, Compound-Hazard Context

The process of adaptation in outdoor recreation takes place at different levels that are based on individual behavioral adjustments to institutional policy change and investment in infrastructure[3]. In the face of rising heatwaves and droughts, adaptation is most conceptualized as a collection of measures that seek to reduce exposure, diminish sensitivity, and enhance adaptive capacity, which is in line with the ESAC framework. The threshold nature of recreation effects causes the necessity of change: the risk of heat illness rises exponentially above some level of heat stress, and drought-induced limitations may suddenly limit opportunity when hydrologic and water-quality thresholds are exceeded. In addition, the increasing number of compound hazards implies that individual-hazard adaptations are inadequate. Measures oriented to the reduction of heat exposure might be ineffective to prevent the risk of smoke inhalation, and water-oriented measures might not work when heat promotes the overlapping demand peaks and quality loss. As a result, it is important to note that adaptation planning is focused less on the seasonal and more on the multi-hazard-based decision-making and dynamic operations[72].

6.2. Visitor-Level Adaptations: Behavioral Change, Protective Practices, and Constraints

The main way of acclimatizing to heat, which recreationists use, is to change activity timing to cooler periods, decline intensity or duration, augment hydration, choose shady paths, and/or replace by destinations with greater elevation, coastal, or water proximity[31]. These measures may help reduce exposure and sensitivity, especially where people are knowledgeable and well-adapted to take them. Other protective measures are also encompassed, such as acclimatization, dressing, electrolyte regulation, and the use of cooling mechanisms like wetting, misting, or portable shade. In the case of drought, the visitors can replace the activities that are not directly related to water-based recreation in case of its limited access, change to other bodies of water, or lower the expectations of experiences that are not as reliant on water availability and high ecological standards.

The visitor-level adaptation is, however, limited by the unequal access to information, resources, and substitution options. The time-shifting can be impossible in the case of people who cannot alter their working schedule, and the substitution of destinations can demand healthier transport and money. The role of risk communication and heat-health literacy on whether the adaptation is proactive or reactive is dependent on their post-adverse experience. Besides being noted, behavioral adaptation may produce group outcomes that demand managerial consideration, such as crowding at thermal refugia, concentrated effects at the remaining accessible water locations, and more intergroup conflict among user groups competing over the small safe space. These limitations imply that visitor adaptation cannot be seen as a one-size-fits-all solution, but rather it should be complemented by site-level interventions and governance regimes that facilitate safe decisions and reduce the number of displaced effects [73].

6.3. Site- and Manager-Level Adaptations: Infrastructure, Operations, and Risk Communication

Adaptation strategies at the site and agency level can be broadly grouped into three and these include infrastructure and design, operational management, and communication and decision support. Physical interventions which minimize heat exposure are planting more shade where vegetation is ecologically suitable, planting shade structures at busy nodes, better access to drinkable water by installing refill stations, and better access to cooling at visitor centers and transit centers [74]. Design considerations in trail networks might involve rerouting or hardening those portions of the trail network subject to extremely high radiant loads or drought-induced erosion, better signage at crossings, and the ability to access emergency services in high-hazard areas. In the case of campgrounds, adaptations are usually of shade presence, night comfort, water supply reliability, and management of tree risk in drought stressed stand.

Adaptations in operations comprise dynamic shutdowns or restrictions during heat waves, adjusted operating times, timed access controls in an attempt to counter overcrowding, staffing, and medical preparedness modifications [32]. Drought stage models in water environments can initiate restrictions according to the elevation of the reservoir, streamflow levels, or water quality indicators, and can be combined with instant updates to notify users of ramp usability, navigability, and bloom warnings. An important consequence of the threshold-based vulnerability is that the rules of operation should be explicitly connected to the measurable indicators and be presented in a manner that can be predicted by users, but at the same time be adaptable enough to adapt to the fast-changing environment.

Risk communication is one of the key adaptation levers as it has the power to change behavior and minimize avoidable incidents [10]. When properly managed, effective communication will combine understandable descriptions of hazards, helpful guidance, and prompts that are provided based on activity type and level of experience. To maximize the latter, messages that map conditions into exertion-specific advice, point out early symptoms, and address risks that are particular to the route can enhance effectiveness in the case of heat. In the case of hazards related to drought, access restrictions, water quality alerts, and fire restrictions can be communicated in time to avoid unnecessary travel and prevent risky substitution. The most effective communication channel to use is a combination of channels, like on-site signage, digital platforms that are used to plan trips, and collaborating with tourism operators and event organizers. Notably, communication should be developed in an inclusive way that takes into consideration language access, the level of outdoor experience, and disparity in access to real-time information.

6.4. Governance and Cross-Sector Coordination: Integrating Parks, Public Health, Water Management, and Emergency Services

Most of the most important adaptations cannot be coordinated at a single location. Risks of heat and drought overlap with the public health systems, water allocation institutions, and emergency response networks, and recreation management is becoming more and more reliant on these external systems. A combination of heat-health warning systems and parks and secure zones may help to maintain a consistent threshold and coherent communication, especially in the case of urban parks serving as cooling shelters. On the same note, water governance choices on drought response are in many cases determined by decisions on reservoir releases, minimum flows, and restrictions aimed at protecting the ecosystem, which directly impact recreation opportunity and safety [75,76].

The other vital aspect of dealing with the hazards of compound wildfire smoke is the cross-sector coordination [77]. Consistent heat stress and air quality warnings will lessen confusion and assist visitors in making more reasonable choices than separate, possibly rival messages. The coordination of emergency services becomes more relevant in times of extreme situations as the search-and-rescue demand levels can increase, whereas staffing is limited. Adaptive capacity requires flexibility in the regulations at the governance level, a distinct authority in dynamic closures, and the capacity to deploy resources expeditiously to risky locations, at the governance level. Such institutional issues are usually not taken into account in the quantitative vulnerability models, but they have a powerful impact on the seen results and the possibility of adaptation.

6.5. Limits to Adaptation and the Risk of Maladaptation

There is a limit to adaptation, especially in extreme situations, in the case of compound events, and where exposure to climate is increasing at a rate that is more rapid than changes in operational and infrastructural adaptation [6]. No matter the messages or facilities, there are physiological limitations to safe participation that include high heat stress under any circumstances of intense exertion. In drought-prone basins, water availability can be limited by the structure of the competitive demands and ecological protection needs that restrict the degree to which recreation can be served with releases or infrastructure alterations. Exposure to smoke can also make outdoor activity unsafe despite having adaptations to heat, making the investments with the assumption of prolonged use in the summer seasons less useful.

When the interventions minimize the risk in one dimension and increase it in others or when they result in inequitable outcomes, the issue of maladaptation is a major one [78]. Indicatively, the development of infrastructure to offer shade and water may augment the pressure of visitation in the ecologically sensitive places without capacity management. Equally, any system or measure that can guarantee safety and resource protection can encourage diversion of usage to non-managed sites, where it is riskier to the environment. Pricing and capacity management can also make access less available to lower-income users or communities with few options, making a safety adaptation an equity injury. Since interventions may redistribute risk, **Table 4** presents a summary of the important adaptation choices as well as tradeoffs, equity implications, and a practical evaluation measure. The risks have pointed out the necessity of adaptation evaluation frameworks that factor in system-wide displacement, environmental tradeoffs, and distributional outcomes as opposed to the benefits of sites alone.

Table 4. Adaptation options for heat- and drought-related recreation risk, including tradeoffs, equity implications, and evaluation metrics.

Adaptation Type	Example Intervention	Primary Risk Reduced	Potential Trade-offs/Maladaptation	Equity Implications	Suggested Evaluation Metric(s)
Visitor-facing information	Integrated heat–smoke–water advisories; route-specific warnings	Exposure via safer decisions	Information overload; unequal access	Language/tech barriers; differential trust	Message reach/comprehension; behavior change indicators
Heat exposure infrastructure	Shade structures; water refill stations; cooling refuges	Heat strain sensitivity	Concentrates use; ecological impacts	Who benefits depends on access and fees	Incidents/SAR rates; use redistribution; satisfaction
Operational controls	Dynamic closures; timed entry; altered hours	Acute safety risk	Displacement to unmanaged sites	Permits/pricing may reduce access	Compliance; displacement patterns; incident reduction
Water-access management	Ramp updates; flow-based restrictions; alternative launches	Injury/access failures	Shifts pressure to fewer water bodies	Transport barriers to alternatives	Trip success rates; conflicts; safety incidents
Ecosystem/asset protection	Trail hardening; reroutes; tree-risk management	Safety + resource degradation	Infrastructure footprint	May favor flagship sites over local parks	Maintenance costs; erosion; hazard incidents
Governance coordination	Align parks with public health and water agencies	Multi-hazard response capacity	Institutional complexity	Can improve consistency and access	Response time; closure decision consistency; outcome equity

6.6. Evaluating Adaptation Effectiveness: Metrics, Learning, and Accountability

The most consistent gap in the literature is the lack of strict trials concerning the effectiveness of adaptation. Most of the adaptations are made in the form of pragmatic actions to perceived risk that is not systematically evaluated in terms of whether it decreases incidents, increases comfort and satisfaction, or moves behavior towards a safer option. The assessment needs to have well-defined outcome measures, controls, and procedures that would enable them to differentiate between adaptation effects and the background variability in climate and visitation. In the case of heat-focused interventions, it is relevant to use changes in the incident rates, demand in the emergencies, route choice, and time-of-day, and visitor knowledge and self-reported preparedness. To address the issue of droughts, assessment can rely on the decreased number of access-related conflicts, enhancement of regulations adherence, changing the trip replacement patterns, and the rate of exposure to poor water quality conditions. Adaptations that are based on communication are also central to process metrics, including message reach, comprehension, and trust [20,79].

Learning-based management styles are quite appropriate in this setting since they approach interventions as a hypothesis, which is to be tested and refined. Monitoring the microclimate conditions at high-risk nodes, tracking closures and restrictions, and incorporating incident information can be part of adaptive management to determine where to change the thresholds and where the infrastructure investments most benefit the marginal. Other learning loops can assist agencies in their prediction of changing seasonality, since the recreation demand could shift in shoulder seasons when the risk of heat is less, and this may cause new demands and staffing requirements that are not related to the past peak seasons [8,80].

6.7. Priority Research Agenda for Actionable, Equity-Aware Vulnerability Assessment

Research priorities in the future are based on the limitations of evidence and methodological issues identified in previous sections. An initial point of action is to harmonize the hazard definitions and thresholds, especially of heatwaves and drought, to enhance comparability between sites and studies. This involves increased application of heat stress indices that absorb humidity and radiation and associate drought signals with operationally significant hydrologic and water-quality levels. The second priority is enhanced attribution of causality during compound hazards. Research that has the potential to unravel the role of heat, drought, smoke, and management activities on visitation and safety impacts will offer a more competent foundation to predict and design adaptation [40,81].

Thirdly, promoting site-scale exposure assessment, such as microclimate mapping on trails and day-use nodes and combining exposure estimates with the intensity of activity and the difficulty of trails, is a priority. This is necessary in order to translate climate information into actionable advice to visitors and trigger managers. Fourthly, there is a need to integrate equity in measurement and evaluation. Differential exposure and coping capacity across user groups and workers should be manifested in vulnerability assessments, and distributional effects of closures, permits, pricing, and infrastructure investments should be assessed through adaptation evaluations. A fifth priority is improved depiction of the dynamics of displacement and substitution because it acknowledges that behavioral adaptation can change risk both spatially and socially. Last but not least, integrating data further, integrating climate/hydrologic observations with mobility observations, incident observations, and qualitative evidence, represents a way forward towards more comprehensive, operationally relevant vulnerability assessments, as long as the issues of privacy, representativeness, and interpretability are resolved [82–84].

6.8. Toward Decision Support: From Indicators to Triggers and Integrated Advisories

Vulnerability assessment has a pragmatic importance in its ability to make decisions. The synthesis of this review indicates that the decision support needs to translate indicators into triggers that are transparent, context-specific, and compound-hazard triggers. This can be done in practice by choosing heat and drought levels that are associated with significant changes in safety, access, or experience; linking these levels with operational responses that are predetermined; and conveying information via communication channels relevant to how individuals organize trips and perceive risk. A combination of heat stress, water access, water quality, and smoke advisories can be used in order to minimize the confusion and enable safer decisions as compared to single-hazard advisories. The most effective systems in the future are probably those that tie monitoring and evaluation together so that agencies and communities may rapidly adjust thresholds, target investments, and trade safety, access, conservation, and equity goals to increasingly variable and extreme conditions [21].

7. Conclusions

The increasing frequency and severity of heatwaves, combined with prolonged and severe drought conditions, are increasingly influencing outdoor recreation. In recreation systems, vulnerability is not the result of an increase in temperatures or a decline in water levels, but rather a combination of the interaction between the hazards and physiological limits, hydrologic and infrastructure limitations, ecosystem behavior, and institutional decision-making. Extreme temperatures increase direct risks to human health and safety, particularly when performing activities of high effort and in places with little shade, water, or emergency access, and drought limits the opportunity to rely on water by setting up sudden access standards and escalating indirect routes, like poor water quality, reduced ecological and scenic values, and an increase in exposure to wildfires and smoke. The increasing occurrence of compound and cascading occurrences implies that most disruptive effects tend to be experienced where heat, drought, smoke, and management restrictions interact, thus creating nonlinear changes in participation, safety events, and operational capacity.

The synthesis above highlights the usefulness of framing exposures of outdoor recreation vulnerability using the Exposure Level Sensitivity Level and the Adaptive Capacity. This framework explains why vulnerability varies systematically by activity and region, and why the analysis of averaged conditions is blind to the extreme, threshold-crossing conditions that lead to closures, medical crises, and the sudden loss of an opportunity. Activities involving trails and endurance are most likely to be subjected to exertional heat stress and microclimatic heterogeneity, whereas recreation based on water is especially susceptible to hydrologic limits and water-quality mediated health hazards. Both camping and viewing the natural world are vulnerable to immediate thermal discomfort, particularly on warm nights, as well as more protracted drought-induced ecosystem transformation that transforms the attractiveness and safety characteristics of destinations (e.g., tree death, fire closures). The agencies of protected areas and parks are in a central position, which means that they transform the conditions of hazards into active operation forms that can be used to mitigate risk or to relocate it to other locations and user cohorts.

Methodologically, the literature is a developing arsenal of approaches to measure vulnerability, but comparability and decision usefulness are limited by imprecise definitions of hazards, scale incompatibilities, and little capacity to attribute the observed results under conditions of compound hazards. Anomalies of air temperature and precipitation seldom reflect the factors of interest to recreation and recreation-relevant heat stress indices (e.g., WBGT, UTCI), and hydrologic/water-quality thresholds are not always used. Outcome measurement is also still imbalanced: visitation and revenue impacts are more commonly measured compared to health and safety outcomes, and ecological pathways are commonly inferred, not directly connected with measures of recreation experience. The gaps are also consequential since the managers require strong, location-specific information regarding when and where the risk rises, and what interventions may be expected to lessen the harm and the impacts of adaptation on access and equity.

The opportunities for adaptation are high but limited. Changes in visitor behavior, such as time shifting, route replacement, hydration, and cooling behavior, can help lessen exposure to people with flexibility and knowledge, but may also choose to concentrate use in thermal refugia and place pressure on the remaining water-access sites during a drought. Interventions of a site and agency level, such as shade and water facilities, microclimate-based trail design, real-time warnings, and dynamic restrictions, can significantly mitigate risk in combination with a clear threshold and communication plan. Nevertheless, extreme compound extremes might surpass the infrastructure and operational readiness and lead to closures and cancellations of events. These facts enhance the significance of governance and cross-sector coordination between parks, agencies in charge of public health, water managers, and emergency services to coordinate triggers, messages, and resource mobilization in extreme times.

Lastly, it is presented in this review that vulnerability and adaptation are distributed in their nature. The exposure, sensitivity, and adaptive capacity vary among visitors, workers, and communities, and the adaptation measures can have inequitable effects in cases where the adaptation actions are based on pricing, permits, or closures, which limit access without offering accessible alternatives. Equity, as a fundamental aspect of vulnerability assessment and not an appendix, should be considered by future research and practice. The way forward will be in agreeing on definitions and thresholds of heat waves and droughts in recreation, enhancing site-scale exposure characterization with microclimate data and route-level modeling, effective causal attribution under multi-hazard conditions, and an assessment of adaptation effectiveness with measures that reflect safety, quality of experience, displacement, and distribution effects. As outdoor recreation remains an important source of health, cultural bond, and economic initiative, it will be important to create operationally applicable and equity-conscious vulnerability appraisals as a means of maintaining safe and resilient recreation opportunities in an increasingly hotter, drier, and hazard-coupled future.

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