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From ISO 14091 to a New Standard for Social-Ecological Vulnerability Assessment: Bridging Gaps in Climate Adaptation

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Abstract

The escalating threats of climate change, including rising sea levels and intensified extreme weather events, demand immediate and comprehensive adaptation strategies. Social-ecological systems (SES), characterized by their intricate interdependencies between human societies and natural ecosystems, are particularly vulnerable to these changes. Current frameworks, such as ISO 14091, provide valuable tools for assessing climate-related risks but fall short in capturing the dynamic feedback loops, integrated vulnerabilities, and cross-sectoral interconnections of SES. This paper identifies critical gaps in ISO 14091, including its sectoral focus and limited systems-based perspective, and proposes a roadmap for developing an international standard tailored to SES vulnerabilities. The framework emphasizes interdisciplinarity, inclusivity, and adaptability, integrating tools like impact chains, participatory approaches, and scenario modeling to enable holistic, context-specific, and globally relevant assessments. By addressing these gaps, the proposed standard aims to enhance resilience, reduce cascading risks, and empower diverse stakeholders to implement sustainable climate adaptation strategies for SES worldwide.

Keywords Social-Ecological Systems (SES), Climate Change Adaptation, Vulnerability Assessment, Resilience Building, Integrated Frameworks

Introduction

The escalating impacts of climate change, such as rising sea levels and intensifying extreme weather events, highlight the urgent need for comprehensive strategies that not only mitigate risks but also enhance resilience [1]. A critical aspect of this challenge lies in the vulnerability of social-ecological systems (SES), which are characterized by the interconnected and dynamic relationships between human societies and the natural ecosystems upon which they depend [2]. SES vulnerabilities manifest in cascad-

ing effects, where disruptions in one part of the system trigger a series of consequences throughout the system [3]. For instance, ecological disruptions such as deforestation can result in the loss of ecosystem services, which subsequently decrease agricultural productivity and lead to social outcomes such as poverty, food insecurity, and migration. On the flip side, socio-political instability, including poor governance or conflict, can exacerbate ecological degradation by undermining sustainable resource management practices, creating a vicious cycle that fur-



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ther destabilizes both social and ecological systems [4]. Despite the clear interdependence between social and ecological dimensions, existing climate adaptation frameworks often adopt siloed approaches, addressing social or ecological vulnerabilities independently [5]. This fragmentation presents a significant challenge, as it fails to adequately account for the interactions and feedback loops that define SES. For instance, climate change-induced impacts on ecosystems can directly affect human populations, particularly in areas where livelihoods are heavily dependent on natural resources. Similarly, societal factors such as governance, economic stability, and social equity can influence the capacity of ecosystems to adapt to or recover from climate stressors [6]. Hence, it is essential to recognize the dynamic interplay and feedback loops that exist between ecological and socioeconomic-ecological systems, as emphasized by research findings [7]. These feedback loops underscore the interconnectedness and mutual influence between the natural and socioeconomic dimensions, reinforcing the importance of an integrated approach to vulnerability assessment. The absence of a holistic approach to addressing these interconnected vulnerabilities hampers the effectiveness of adaptation strategies, resulting in measures that may be ill-suited to addressing systemic vulnerabilities within SES [8]. This underscores the need for frameworks that integrate both social and ecological dimensions to effectively assess and manage climate risks.

While international standards such as ISO 14091 [9] provide valuable methodologies for assessing climate-related risks, they fall short in their application to SES. ISO 14091 focuses on evaluating exposure, sensitivity, and adaptive capacity through tools such as impact chains and participatory approaches, yet it does not explicitly incorporate the dynamic feedback loops inherent in SES. These feedback mechanisms, where changes in one component (such as ecological health) influence other components (like social stability), are critical to understanding the full range of vulnerabilities within SES. Furthermore, ISO 14091's emphasis on sectoral assessments does not fully address the complex interrelationships between ecological and social systems, limiting its utility in assessing vulnerabilities within SES that require cross-sectoral and systems-based thinking. The need for a dedicated international standard specifically designed to assess SES vulnerabilities is thus evident. Such a standard would unify methodologies for assessing and addressing the risks associated with SES, ensuring that adaptation strategies are not only comprehensive but also inclusive and adaptive. This paper aims to explore the conceptual and practical requirements for the development of such a standard. It will build upon the foundations of ISO 14091, extend-

ing its framework to incorporate a more systems-based approach that addresses the complexities and feedback loops inherent in SES.

The objectives of this paper are threefold:

1. To analyze the applicability of ISO 14091 to SES vulnerability assessment, identifying areas where the standard can be expanded or adapted to better address the unique challenges of SES.
2. To identify the critical gaps and challenges in existing SES vulnerability assessment frameworks, such as the lack of integration between social and ecological dimensions and the absence of comprehensive feedback mechanisms.
3. To propose a roadmap for developing a dedicated international standard tailored to SES vulnerabilities, providing a clear pathway for integrating social and ecological considerations into climate adaptation planning.

Through these efforts, this paper aims to empower stakeholders at all levels to better integrate SES considerations into climate adaptation planning. The development of a dedicated standard for SES vulnerability assessment will help to foster resilience and sustainability in a rapidly changing world, ensuring that both human and ecological systems are able to adapt to the challenges posed by climate change.

2. Literature Review

2.1 Methodologies

Social-ecological systems (SES) are at the heart of the challenges we face in the age of climate change. These systems are not just intertwined but deeply interdependent—human societies and the ecosystems we rely on are connected in ways that make them both resilient and vulnerable [7]. Understanding the vulnerability of these systems is more critical than ever, as the effects of climate change continue to intensify. From rising sea levels to devastating storms, these changes pose serious risks to ecosystems and the communities that depend on them [10]. This literature review explores the evolving methodologies for assessing the vulnerability of SES and highlights the crucial role of climate change adaptation planning.

At its core, vulnerability refers to how susceptible a system is to harm due to climate-related hazards and how capable it is of adapting to those impacts. In the context of SES, vulnerability is defined by three key factors: exposure, sensitivity, and adaptive capacity [10]. Exposure is the degree to which a system is subject to climate hazards; sensitivity measures how affected the system will be by those hazards; and adaptive capacity is the ability of the system to cope, adjust, and minimize negative impacts [8]. However, what makes vulnerability in SES

particularly complex is that these dimensions are deeply interconnected. The impact of climate change on one part of the system can cascade and amplify throughout the entire system. For example, deforestation (an ecological disruption) can reduce agricultural productivity (a social consequence), leading to poverty and migration.

It is essential to view vulnerability as a dynamic, evolving process, shaped not only by climate change but also by the social and ecological relationships within the system [11]. Over the years, the literature has increasingly acknowledged the need to move beyond siloed approaches—where social and ecological factors are assessed independently—toward a more integrated, systems-based approach. This shift enables us to understand how social systems exacerbate ecological degradation and how, conversely, ecological disruptions can amplify social vulnerabilities. The resilience of social-ecological systems hinges on addressing these interdependencies, ensuring that both human and ecological components are considered in vulnerability assessments [12].

The complexity of social-ecological systems demands innovative methodologies capable of capturing both the ecological and social dimensions. Over the years, researchers have developed a range of approaches to better understand and assess vulnerability in these systems, each offering unique insights [13]. Impact Chain Analysis is one such tool that has gained prominence in recent years. By mapping the cause-and-effect relationships between climate hazards, ecological impacts, and social outcomes, impact chain analysis helps reveal how disturbances in one part of the system can trigger a domino effect, impacting other components [14]. For instance, a heatwave may lead to reduced crop yields, which can drive economic losses, increase poverty, and ultimately lead to social unrest. By tracing these connections, impact chains allow us to identify the most vulnerable points in a system and prioritize interventions [14]. This method provides not just a static snapshot of vulnerability but a dynamic, interconnected map of risks across the system. Integrated Assessment Models (IAMs), which combine data from ecological, economic, and social sectors, are another powerful tool for vulnerability assessment [15]. IAMs simulate the impacts of climate change under various scenarios, offering valuable insights into long-term risks and potential adaptation measures (Clarke et al., 2014). These models can provide a broad, quantitative understanding of vulnerability but are often criticized for not accounting for the qualitative, context-specific insights that come from local knowledge.

2.2 Participatory Approaches

That's where participatory approaches step in. These

methods, which actively involve stakeholders—especially local communities—are essential for capturing the unique, on-the-ground vulnerabilities that IAMs might miss [16]. By integrating local knowledge, these approaches not only enhance the accuracy of vulnerability assessments but also ensure that the adaptation strategies are socially inclusive and contextually appropriate. Engaging local communities in the process fosters empowerment, ownership, and more sustainable, long-term solutions to the challenges posed by climate change [17]. The social dimensions of vulnerability are as critical as the ecological ones, and in many ways, they are more immediately impactful [18]. Vulnerability is not evenly distributed within or between societies. Certain groups—such as marginalized communities, indigenous peoples, women, and the poor—are disproportionately affected by climate change due to their limited access to resources, political power, and decision-making processes. Equity and social justice are, therefore, an essential element in vulnerability assessments. Vulnerability is often exacerbated for marginalized groups, including indigenous peoples, women, and low-income communities, due to their limited access to resources and decision-making processes [18]. In particular, adaptive capacity plays a key role in social vulnerability. The capacity of a community to adapt to climate change is influenced by a variety of factors, including governance, education, access to technology, and financial resources [19]. Communities with strong social networks, equitable access to resources, and effective governance structures tend to have higher adaptive capacities [19]. However, in many developing regions, weak governance and resource constraints hinder the ability of communities to effectively adapt to climate change [20]. Understanding and enhancing adaptive capacity is, therefore, a central goal of vulnerability assessments and climate adaptation planning.

The ecological dimension of vulnerability focuses on how ecosystems respond to climate stressors and the implications of these responses for social systems [21]. Climate change has a profound impact on ecosystems, including shifts in species distributions, biodiversity loss, and the degradation of ecosystem services. These ecosystems provide essential services—such as food production, water purification, and carbon sequestration—that are critical to both ecological and human well-being [22]. Ecological resilience refers to the ability of an ecosystem to absorb disturbances and recover [23]. However, ecosystems often face tipping points where repeated stressors push them beyond their ability to recover, resulting in irreversible changes [24]. Vulnerability assessments must account for these thresholds to accurately assess the risks to ecosystems and the services they provide.

Adaptation to climate change involves a range of strategies aimed at reducing vulnerabilities and enhancing resilience in SES. The integration of vulnerability assessments into adaptation planning is essential for identifying the most pressing risks and determining appropriate actions to mitigate these risks [25]. Adaptation strategies can be categorized into autonomous and planned adaptation. While autonomous adaptation involves individuals or communities taking spontaneous actions to cope with climate impacts, planned adaptation refers to deliberate, policy-driven interventions designed to reduce vulnerability and enhance adaptive capacity [26]. Examples of planned adaptation include the restoration of ecosystems, the implementation of early warning systems, and the construction of resilient infrastructure. One of the greatest challenges in adaptation planning is mainstreaming adaptation into existing policies and development frameworks [27]. Mainstreaming ensures that climate change considerations are incorporated into all aspects of development—such as agriculture, health, infrastructure, and urban planning—thus making resilience an integral part of long-term development goals [28]. This requires strong governance, coordination across sectors, and the mobilization of resources to implement adaptation measures effectively.

2.3 Gaps in Current Frameworks

Despite advances in vulnerability assessment methodologies, several challenges remain. One of the main challenges is the lack of data, particularly in developing countries where climate impacts are often most pronounced [29]. Accurate data on both social and ecological dimensions of vulnerability is essential for comprehensive assessments. There is also a need for more context-specific methodologies that can capture the unique characteristics of different SES. Furthermore, while frameworks like ISO 14091 provide valuable guidance, there is a growing need for more integrated approaches that simultaneously consider social, ecological, and governance dimensions. The assessment of vulnerability in social-ecological systems is a dynamic and critical component of climate change adaptation planning. Understanding the complex, interconnected nature of social and ecological vulnerabilities is essential for designing effective and inclusive adaptation strategies [30]. By employing a variety of methodologies—from impact chain analysis and integrated assessment models to participatory approaches—vulnerability assessments can provide the insights needed to build resilient communities and ecosystems. The challenges in vulnerability assessments are significant, but by addressing them with innovative tools, promoting equity, and strengthening adaptive capacity, we can en-

sure a more sustainable and resilient future for all [31]. Adaptation is not just a response to climate change—it is an opportunity to build a better, more resilient world for current and future generations.

3. Insights from ISO 14091

ISO 14091:2021, Adaptation to Climate Change—Guidelines on Vulnerability, Impacts, and Risk Assessment, provides a systematic framework for assessing climate change risks and vulnerabilities across various systems. It emphasizes transparency, inclusivity, and the integration of both qualitative and quantitative data, making it an essential tool for organizations engaged in climate change adaptation planning. The standard focuses on identifying the exposure, sensitivity, and adaptive capacity of different systems, offering methodologies such as impact chains and scenario-based planning. These tools help assess how climate change may affect systems, identify vulnerabilities, and prioritize adaptive actions to reduce risks.

One of the key strengths of ISO 14091 lies in its structured approach to vulnerability assessment, which is highly relevant for evaluating social-ecological systems (SES). SES are complex, interconnected systems composed of both human and ecological components, making them particularly challenging to assess. ISO 14091's use of impact chains is particularly valuable in this context. Impact chains provide a visual representation of the cause-and-effect relationships within systems, helping to map how climate stressors (such as flooding or drought) influence ecological processes, which in turn impact human communities and their livelihoods [9]. This approach facilitates the identification of vulnerabilities across both ecological and social dimensions, making it possible to prioritize actions that address these vulnerabilities in a coordinated manner. Additionally, the standard places a strong emphasis on participatory approaches, ensuring that a wide range of stakeholders, including local communities, are involved in the assessment process. This inclusivity is vital in SES assessments, as local knowledge and experiences are often critical in understanding the true nature of vulnerabilities and adaptation needs. By integrating these context-specific insights, ISO 14091 supports the development of more effective and locally relevant adaptation strategies. Furthermore, the standard promotes the use of indicator-based assessments, encouraging the selection of metrics that are tailored to the specific region or sector. This flexibility allows practitioners to assess vulnerabilities in ways that are appropriate for the unique characteristics of each SES.

Despite these strengths, ISO 14091 has limitations when applied to the assessment of SES. One of the primary

challenges is its fragmented approach. The standard is designed to address organizational risks, with a focus on individual sectors or systems, but it lacks a systems-based perspective necessary for understanding the interconnected nature of SES. In SES, the relationships between human and ecological components are bidirectional, meaning that disruptions in one area can cascade through the system and affect other components. For example, ecosystem degradation can lead to reduced agricultural productivity, which in turn may increase social vulnerability. ISO 14091 does not provide adequate methodologies to assess these feedback loops between social and ecological components, which are critical to understanding the full scope of vulnerability in SES. Another significant limitation is the data reliance inherent in ISO 14091. The standard assumes access to robust, high-quality data across ecological and social dimensions. However, in many regions, especially in resource-constrained areas, data may be sparse or inconsistent, making it difficult to carry out comprehensive vulnerability assessments [9]. Inadequate data can limit the accuracy and effectiveness of adaptation strategies, highlighting the need for improved data infrastructure and more accessible data-sharing mechanisms. These limitations underscore the need for a specialized framework that builds upon the strengths of ISO 14091 while addressing the unique challenges of SES. Such a framework would need to integrate systems-based methodologies, account for feedback loops, and ensure that data gaps do not hinder the assessment process. Developing this framework is essential for improving the effectiveness of climate change adaptation efforts and enhancing resilience in vulnerable social-ecological systems.

4. Challenges in SES Vulnerability Integration

Social-ecological systems (SES) are inherently complex due to their dynamic feedback loops and interdependent interactions between human and ecological components. For example, overfishing, a social behavior, leads to the depletion of marine ecosystems, which in turn reduces the availability of fish, ultimately impacting the livelihoods of those who depend on fisheries. This reduction in resources not only affects local communities but also triggers broader social consequences, such as increased poverty and migration pressures. These cascading effects highlight the need for advanced models capable of simulating the complex interactions within SES across multiple scales [32]. Such models must account for ecological dynamics, such as changes in biodiversity, and social systems, including economic dependence on natural resources. However, current frameworks often fail to integrate these complex interactions, which limits the ability to predict or manage SES vulnerabilities effectively [33].

One of the primary obstacles to comprehensive SES assessments is the significant data gaps that persist, especially in developing regions. Ecological data, such as biodiversity indices, species health, and ecosystem service provision, are often incomplete or inconsistent, making it difficult to assess the true state of ecosystems [34]. Similarly, social data, including governance metrics, income distribution, and community resilience, is often outdated or scarce [35]. These data gaps complicate vulnerability assessments and the development of effective adaptation strategies. To overcome these challenges, international collaboration and substantial investment in data infrastructure are essential. Standardizing and harmonizing data collection methods across regions, as well as enhancing data-sharing mechanisms, are necessary steps to ensure that accurate and up-to-date information is accessible to all stakeholders, including policymakers, researchers, and local communities [36].

Another critical challenge is the exclusion of marginalized groups, including indigenous communities and local stakeholders, from vulnerability assessments [37]. Indigenous and local knowledge systems offer valuable insights into the functioning of SES, often based on centuries of experience in managing ecosystems sustainably [37,38]. However, these knowledge systems are frequently underrepresented in formal scientific assessments and policy-making processes. The failure to integrate these perspectives can lead to adaptation strategies that are not contextually appropriate or socially acceptable, particularly in culturally diverse areas [39]. Engaging marginalized groups in the decision-making process is vital for developing adaptation strategies that are both effective and equitable, ensuring that all voices are heard and that strategies are relevant to the communities they aim to protect. Frameworks for assessing SES vulnerability often rely on abstract concepts such as resilience, adaptive capacity, and exposure. While these concepts are crucial for understanding the dynamics of SES, translating them into actionable indicators and strategies remains a significant challenge [40]. Bridging the gap between theory and practice requires the development of practical tools and methodologies that enable the application of these concepts in real-world contexts. Without clear metrics and frameworks for implementing these theoretical concepts, vulnerability assessments can remain theoretical exercises with limited practical impact [41].

SES vulnerabilities are shaped not only by climate-related stressors such as rising temperatures and extreme weather events but also by non-climatic factors, including economic instability, governance failures, and social inequality [42]. Focusing solely on climate-induced risks while neglecting these non-climatic stressors undermines

the comprehensiveness of vulnerability assessments and adaptation strategies. Non-climatic factors often exacerbate the impacts of climate change, as seen in areas where weak governance systems prevent effective climate adaptation or where economic instability prevents the implementation of long-term resilience-building strategies [43]. An integrated approach that addresses both climate and non-climate stressors is essential for developing robust, comprehensive adaptation strategies.

Static vulnerability assessments, which provide a snapshot of the current state of SES, fail to account for the evolving nature of vulnerabilities over time [44]. SES are dynamic, with changing ecological conditions, shifting socio-economic factors, and evolving governance structures. Additionally, vulnerabilities are not uniform across regions or scales, making it essential to incorporate scenario-based planning and dynamic modeling into vulnerability assessments [45]. These approaches allow for the exploration of future risks under various climate and socio-economic scenarios, helping to identify strategies that are flexible and resilient to change. Without accounting for these temporal and spatial dynamics, vulnerability assessments risk becoming obsolete as new challenges emerge [44].

Finally, resource constraints in many parts of the world, particularly in the Global South, pose a significant challenge to conducting SES vulnerability assessments. These regions often lack the financial, technical, and human resources necessary for comprehensive data collection, modeling, and analysis [46]. Without access to advanced tools and expertise, vulnerability assessments in these areas can be incomplete or inaccurate, limiting the ability to develop effective adaptation strategies. Targeted funding, capacity-building initiatives, and international support are crucial to addressing these disparities. Providing the necessary resources and training will ensure that developing regions can participate in and benefit from global efforts to assess and address SES vulnerabilities.

5. Proposed Framework for SES Vulnerability Standards

The framework for assessing the vulnerabilities of social-ecological systems (SES) is built on three core principles: interdisciplinarity, inclusivity, and adaptability [47]. Interdisciplinarity emphasizes the integration of social, ecological, and governance dimensions, recognizing that SES complexities demand input from diverse fields, such as ecology, sociology, economics, and political science [45]. By incorporating knowledge across disciplines, the framework ensures a holistic understanding of SES vulnerabilities. Inclusivity ensures the active engagement of marginalized communities and stakeholders throughout

the assessment process. This approach captures diverse perspectives, promoting equity and ensuring that adaptation strategies are both contextually relevant and socially just. Adaptability highlights the need for the framework to remain flexible and responsive to changing conditions, acknowledging the dynamic nature of SES vulnerabilities and the need for strategies that can address both current and emerging challenges [33]. The framework's development involves several structured steps. Defining SES components is the first step, which involves mapping the interrelations between social and ecological subsystems while focusing on the feedback loops that drive system dynamics. These mappings highlight the cascading effects of climate and non-climate stressors. Figure (1) delineates a SES vulnerability assessment framework, designed to elucidate the differentiation between ecological and social vulnerability. Serving as a visual glossary, this framework provides a clear interpretation of the interconnection between the two facets of vulnerability. This depiction emphasizes that a comprehensive analysis of social vulnerability requires an understanding of its impact on the ecological system. Initiating the exploration of SES vulnerability involves considering the sensitivity of the social system to hazards occurrences (exposure) and the influence of social-ecological capacity to cope with hazards. The ecological vulnerability of a system to hazards hinges on sensitivity (inherent system characteristics), exposure, and adaptive capacity [48]. Sensitivity, predominantly independent of human influences, reflects the potential for a system to be affected by hazards. Adaptive capacity, essential facets of sustainability in the face of potential disturbances, can be significantly shaped by human-related [48]. Adaptation, an automatic and natural response to SLR, involves functions of both resilience and resistance, with planned adaptation encompassing deliberate actions aimed at enhancing the resilience and resistance of natural systems [48].

The next step is to establish indicators that integrate ecological and social dimensions, enabling comprehensive vulnerability assessments. These indicators help quantify the interdependent risks affecting SES. Incorporating temporal and spatial variability is also critical. Scenario-based tools are used to model long-term changes and regional differences, ensuring that the framework captures the full scope of SES vulnerabilities, both present and future [31]. Finally, developing adaptation pathways translates vulnerability findings into tiered strategies. These pathways include immediate, short-term actions, such as disaster preparedness, and long-term plans, like ecosystem restoration and policy reforms [49]. Several tools and methodologies support these steps. Impact chains help identify and prioritize vulnerabilities, partic-

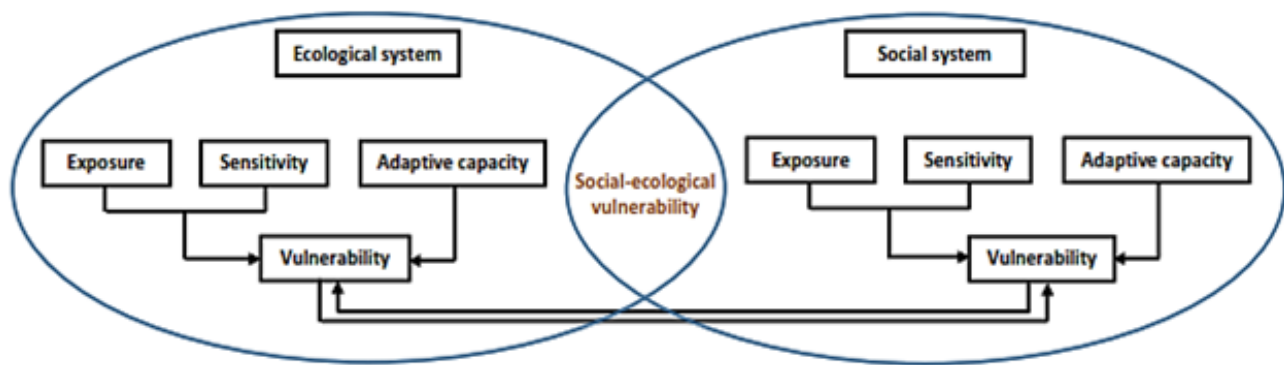


Fig. 1. A conceptual framework for social-ecological vulnerability assessment.

ipatory approaches engage stakeholders to incorporate local knowledge and enhance ownership, and scenario modeling explores future risks and uncertainties [50]. Together, these methods provide a robust, flexible, and inclusive framework for assessing SES vulnerabilities and guiding effective climate adaptation strategies.

6. Integrating Governance into SES Assessments

Governance plays a critical role in shaping the resilience and adaptability of social-ecological systems (SES). Effective governance ensures that resources are distributed equitably, conflicts are resolved efficiently, and adaptive measures are implemented in a way that addresses both ecological and social vulnerabilities [50]. Therefore, it is essential to evaluate governance structures when assessing SES vulnerabilities, as governance decisions often have significant implications for how communities and ecosystems respond to climate change. Key elements of governance integration are as follow:

Stakeholder Representation: An inclusive governance system is crucial for ensuring that all stakeholders, particularly marginalized groups, have a voice in decision-making processes. This inclusivity is vital in SES assessments, as it ensures that adaptation strategies reflect the diverse needs and knowledge systems of affected communities [51]. Marginalized groups, including indigenous populations and economically disadvantaged communities, often possess valuable local knowledge about ecosystem dynamics and resource management. By incorporating their perspectives, governance frameworks can enhance the relevance and effectiveness of adaptation measures.

Policy Alignment: A critical aspect of governance in SES vulnerability assessments is the alignment between national, local, and international policies. Effective governance requires ensuring that national and local policies are consistent with global frameworks, such as the Paris Agreement on climate change and the Sendai Framework

for Disaster Risk Reduction [52]. Alignment with these international agreements ensures that adaptation strategies are in line with global goals and commitments, fostering coherence and shared responsibility across different levels of governance.

Institutional Capacity: The ability of institutions to implement and monitor adaptation measures is a fundamental component of governance integration. This includes evaluating the resource availability, technical expertise, and political stability of institutions responsible for managing adaptation actions [53]. Strong institutional capacity is necessary for effective policy implementation, monitoring progress, and adjusting strategies as needed. In areas with weak governance structures or insufficient resources, adaptation measures may falter, reducing the overall resilience of the SES. Therefore, assessing institutional capacity is essential for identifying barriers and opportunities for enhancing governance effectiveness.

Integrating governance into SES assessments ensures that the systems put in place to manage climate risks are robust, inclusive, and capable of supporting long-term resilience.

7. Financing Mechanisms for SES Adaptation

Adequate financing is essential for the successful implementation of social-ecological systems (SES) vulnerability assessments and adaptation measures. Without sufficient financial support, it is challenging to gather the necessary data, implement adaptation strategies, and build resilience against climate change impacts [54]. This section highlights key financing strategies and examples that can support SES adaptation efforts as follow:

7.1 Public-Private Partnerships (PPPs)

Public-private partnerships (PPPs) are an increasingly important mechanism for financing SES adaptation. These collaborations enable resource-sharing between

governments, private enterprises, and other stakeholders, reducing financial burdens and fostering innovation in adaptation strategies [55]. In PPPs, private sector entities contribute capital, technology, or expertise, while governments often provide regulatory frameworks or subsidies. A notable example is in India, where a PPP facilitated the development of solar-powered irrigation systems [55]. These systems have alleviated water stress by providing sustainable irrigation solutions, while also promoting energy efficiency and reducing dependence on groundwater resources. This partnership model not only addresses environmental challenges but also boosts agricultural productivity, benefiting both local communities and the wider economy. PPPs are an effective way to leverage private sector resources to enhance SES resilience and promote sustainable development.

7.2 International Climate Funds

International climate funds, such as the Green Climate Fund (GCF) and the Adaptation Fund, play a critical role in financing SES adaptation projects, particularly in developing regions [56]. These funds are designed to support projects that address both ecological and social vulnerabilities, ensuring a holistic approach to adaptation. For example, the GCF has supported various mangrove restoration initiatives in Southeast Asia, where coastal communities rely heavily on mangroves for livelihoods, coastal protection, and biodiversity [57]. By funding restoration projects, these international funds help protect critical ecosystems while also improving the resilience of local communities to climate change impacts, such as rising sea levels and increased storm intensities. International climate funds provide crucial financial resources for large-scale, high-impact adaptation projects that might otherwise lack funding.

7.3 Performance-Based Financing

Performance-based financing links funding to the achievement of measurable outcomes, ensuring that funds are used effectively to achieve desired results [58]. This model incentivizes the successful implementation of adaptation measures by tying financial support to specific outcomes, such as improvements in biodiversity health, water availability, or community resilience [58]. For example, in projects focused on reforestation or ecosystem restoration, funding can be contingent on measurable improvements in forest cover or biodiversity indices. Similarly, in social resilience projects, funding may be linked to tangible outcomes like reduced vulnerability to climate-related disasters or improved access to climate information. Performance-based financing ensures accountability and provides transparency, encouraging

more effective use of funds while fostering a results-oriented approach to SES adaptation. These financing mechanisms—PPPs, international climate funds, and performance-based financing—offer innovative and effective solutions to support SES adaptation efforts. By ensuring sufficient funding and aligning financial resources with concrete outcomes, these mechanisms help build resilience and create sustainable solutions for addressing the vulnerabilities of social-ecological systems.

8. Capacity-Building Initiatives

Capacity-building is a fundamental component in equipping stakeholders with the necessary skills, knowledge, and resources to effectively implement SES vulnerability assessments and adaptation strategies [59]. Given the complexity of social-ecological systems and the challenges posed by climate change, it is crucial to enhance the capacity of both local and global actors involved in managing these systems. This section outlines key components of capacity-building initiatives aimed at fostering the skills and infrastructure needed for successful SES adaptation.

8.1 Training Programs

Developing specialized training programs is essential to ensure that practitioners, policymakers, and community leaders have the necessary expertise to carry out effective SES vulnerability assessments and implement adaptation strategies [60]. These training modules should cover the methodologies used in vulnerability assessments, including systems-based approaches, the integration of social and ecological dimensions, and the use of modeling tools to predict future risks. Training should also focus on the practical application of these tools and methodologies, offering hands-on experience with data collection, analysis, and interpretation. Furthermore, training programs should address the unique needs of different stakeholders [61]. For instance, policymakers should be equipped with the knowledge to integrate SES vulnerability assessments into national climate policies, while community leaders must be trained to engage local populations in the adaptation process, ensuring that strategies are contextually relevant and widely accepted. Tailored training programs will build the necessary technical capacity for effective climate adaptation and help ensure that vulnerability assessments lead to actionable outcomes.

8.2 Regional Knowledge Hubs

Establishing regional knowledge hubs is another crucial element of capacity-building. These centers of excellence can provide technical support, facilitate peer learning, and serve as focal points for sharing best practices and lessons

learned [62]. Knowledge hubs should be designed to support local governments, NGOs, and community organizations, offering specialized resources such as research findings, climate adaptation tools, and policy guidelines. Regional hubs can also foster collaboration among different stakeholders, facilitating exchanges of ideas and experiences across geographical regions [62]. For example, knowledge hubs can connect local governments in developing regions with experts in climate science, governance, and adaptation strategies. By promoting cross-sectoral collaboration and knowledge exchange, these hubs can play a pivotal role in scaling up successful adaptation practices and creating a network of experts committed to building resilience in social-ecological systems.

8.3 Community-Led Initiatives

Empowering local communities to lead adaptation projects is essential for fostering ownership and ensuring the sustainability of adaptation measures [63]. Community-led initiatives help ensure that adaptation strategies are rooted in local knowledge and are aligned with the priorities and needs of the people who are directly affected by climate change. Empowering communities involves providing training, resources, and decision-making power to enable them to identify vulnerabilities, design appropriate responses, and implement adaptation measures on the ground [64]. Community-driven projects also enhance social cohesion, as they promote collaboration among local actors, including government agencies, NGOs, and community-based organizations [63]. This inclusive approach ensures that adaptation strategies are not only technically sound but also socially acceptable and culturally appropriate. Furthermore, community involvement increases the likelihood of long-term success by fostering a sense of ownership and responsibility for the outcomes. Together, these capacity-building initiatives—training programs, regional knowledge hubs, and community-led initiatives—create a foundation for effective SES vulnerability assessments and adaptation strategies. By developing the necessary skills, infrastructure, and local leadership, these initiatives help ensure that the proposed standard for assessing and addressing SES vulnerabilities can be successfully implemented, fostering resilience in the face of climate change.

9. Discussion

The proposed framework for social-ecological system (SES) vulnerability assessment represents a significant advancement in addressing the limitations of current methodologies, such as those outlined in ISO 14091. By integrating social and ecological dimensions into a unified, systems-based approach, the framework provides

a holistic tool for climate adaptation planning. Its principles of interdisciplinarity, inclusivity, and adaptability enable the identification of dynamic feedback loops and cascading risks, which are often overlooked in traditional assessments. Tools such as impact chains and scenario modeling further enhance the ability to address both immediate and long-term vulnerabilities, making the framework robust and flexible. The practical implications of this framework are substantial. Policymakers and practitioners can use it to prioritize adaptation measures by identifying vulnerabilities across interconnected dimensions of SES. Additionally, the participatory elements of the framework empower local stakeholders, particularly marginalized groups, ensuring that adaptation strategies are inclusive, context-specific, and culturally relevant. By enabling flexible application across diverse geographic and socio-economic settings, the framework has the potential to bridge the gap between theoretical concepts and practical adaptation measures. Its focus on anticipating cascading risks improves system-level resilience, making it an essential tool for effective climate adaptation planning. Despite these strengths, the implementation of the proposed standard presents several challenges. Data limitations remain a significant obstacle, particularly in developing regions where ecological and social data may be scarce or inconsistent. Without reliable data, comprehensive vulnerability assessments may be difficult to achieve. Additionally, technical expertise and institutional capacity are critical for operationalizing the framework, yet many regions lack the necessary resources and skilled personnel. Addressing these capacity constraints through targeted training and capacity-building initiatives will be essential. Another challenge lies in overcoming institutional fragmentation. Effective SES management requires cross-sectoral coordination, but institutional silos and conflicting policy priorities often hinder collaborative efforts. Strengthening governance structures and fostering coordination between agencies will be crucial for the successful implementation of the framework. Furthermore, while participatory approaches are integral to the framework's design, scaling these approaches across diverse regions and communities can be resource-intensive and logistically complex, requiring innovative strategies and substantial investment. Despite these challenges, the proposed framework offers a transformative approach to SES vulnerability assessment and climate adaptation planning. It opens avenues for further research, including the integration of qualitative and quantitative data, the development of advanced tools for dynamic modeling, and the exploration of innovative financing mechanisms. International collaboration to harmonize data collection and standardize methodologies will also be critical

to enhancing the global applicability and impact of the framework. By addressing these challenges and leveraging its strengths, the framework has the potential to foster resilience and sustainability in social-ecological systems worldwide.

10. Conclusion

The escalating impacts of climate change on social-ecological systems (SES) demand a paradigm shift in vulnerability assessment and adaptation planning. This paper presented a framework that builds on ISO 14091, addressing its limitations and offering a more comprehensive and integrated approach tailored to the complex dynamics of SES. By combining principles of interdisciplinarity, inclusivity, and adaptability, the framework provides a robust foundation for enhancing resilience and fostering sustainable development.

The first objective of this study was to analyze the applicability of ISO 14091 to SES vulnerability assessment. While ISO 14091 introduces valuable tools such as impact chains and participatory approaches, its focus remains largely sectoral, treating social and ecological dimensions in isolation. This study demonstrated the need to move beyond these limitations by integrating systems-based methodologies that capture the feedback loops and cascading effects inherent in SES. By addressing these gaps, the proposed framework significantly enhances the capacity to anticipate and manage interconnected vulnerabilities.

The second objective was to identify the critical gaps and challenges in existing SES vulnerability frameworks. The study highlighted the absence of methodologies to address dynamic feedback mechanisms, inadequate representation of marginalized communities, and the challenges posed by data scarcity in resource-constrained regions. These limitations were addressed by designing a framework that integrates qualitative and quantitative data, emphasizes equity and social justice, and offers practical tools for data-scarce environments. For example, participatory approaches ensure the inclusion of local knowledge, while scenario modeling provides a forward-looking perspective on evolving risks.

The third objective was to propose a roadmap for developing a dedicated international standard for SES vulnerability assessment. The framework provides clear guidance on defining SES components, establishing integrated indicators, and translating vulnerability assessments into actionable adaptation pathways. By combining short-term measures such as disaster preparedness with long-term strategies like ecosystem restoration and governance reforms, the framework ensures a holistic and adaptive response to climate challenges. Furthermore, the

focus on governance and capacity building equips institutions with the resources and skills needed to implement effective adaptation measures, fostering collaboration across scales and sectors.

This study underscores the transformative potential of a standardized approach to SES vulnerability assessment. By addressing the complex interplay between human and natural systems, the framework not only reduces vulnerabilities but also empowers stakeholders to create equitable and context-specific adaptation strategies. The emphasis on participatory methodologies and scenario-based tools ensures that the framework remains relevant and adaptable to diverse contexts, from coastal regions vulnerable to sea-level rise to urban centers grappling with extreme heat events.

Looking ahead, the successful implementation of this framework will require coordinated efforts among international organizations, governments, researchers, and local communities. Investment in capacity-building initiatives, improved data collection systems, and innovative financing mechanisms will be critical to overcoming existing barriers. By fostering collaboration and leveraging shared knowledge, this framework can serve as a cornerstone for building resilience in SES, ensuring that both human and natural systems can thrive in the face of an uncertain climate future.

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Declarations

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Competing interests

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