

Response to comments for “A disaster risk and resilience analysis framework provides insights for modelling natural hazards-induced human mobility”, by Giulia Brutti, Gemma Cremen, and Carmine Galasso

Manuscript #: COMMSENV-25-3747-T

We appreciate the insightful comments provided by the reviewers, which have helped to substantially improve the manuscript. The reviewers' comments are presented below in blue, followed by our responses in black. Excerpts from the revised manuscript are presented in green. Line numbers refer to the clean version of the revised manuscript.

Reviewer #1

Overall Assessment: This perspective paper presents an ambitious conceptual framework for understanding natural hazard-induced human mobility through a capability-based well-being lens integrated with disaster risk and resilience principles. The framework represents a significant conceptual advance over simplified cause-effect models. However, the manuscript would benefit from clearer articulation of operationalization challenges, more critical engagement with the complexity of the proposed framework, and explicit acknowledgment of what can and cannot be modeled with available data.

We sincerely thank Reviewer 1 for their careful and thoughtful engagement with our manuscript. We greatly appreciate the time and attention they devoted to reviewing the work, and we found their feedback extremely valuable in strengthening and further developing the manuscript. Below is our detailed response to their comments.

In summary, we believe we have addressed the Reviewer's general concerns regarding clearer articulation of operationalisation challenges, more critical engagement with the complexity of the proposed framework, and explicit acknowledgement of what can and cannot be modelled with available data.

Comments:

1. The framework integrates multiple theoretical traditions (Sen's capability approach, Nussbaum's central capabilities, Maslow's hierarchy of needs, Bourdieu's forms of capital, resilience theory, risk frameworks). While intellectually rich, this integration creates analytical challenges not sufficiently addressed. For example, Maslow's hierarchy has been criticized for its Western-centric assumptions and lack of empirical support for strict sequential ordering (Wahba & Bridwell, 1976). How does your framework handle cases where self-actualization needs (e.g., maintaining cultural practices) override physiological needs in mobility decisions, as documented in some Indigenous communities resisting relocation despite extreme hazard exposure? The statement "the hierarchy is not strictly sequential" (lines following Table 1) acknowledges this but doesn't explain how the model would operationalize non-sequential need fulfillment.

We thank the Reviewer for highlighting these important challenges. We agree that Maslow's hierarchy of needs is not universally applicable and that this limitation was not sufficiently dealt with in the original manuscript. We clarify this limitation in the revised manuscript, acknowledging that there is cultural and contextual variability in the prioritisation of needs. To address this limitation, our framework adopts Maslow's need categories as independent dimensions rather than a rigid hierarchy; this is now explicitly stated in the text.

The additional text in question reads as follows ([lines 162-166, page 7](#)):

Maslow's pyramid has been criticised for being ethnocentric and for enforcing a strict sequential ordering of needs that lacks empirical support (Hofstede, 1984; Wahba & Bridwell, 1976). To establish a more universally representative framework for objective well-being, we adopt Maslow's need categories as independent dimensions rather than a rigid hierarchy (**Figure 1**).

To avoid the suggestion of a rigid hierarchy, we have also removed the pyramid from Figure 1.

Page 9:

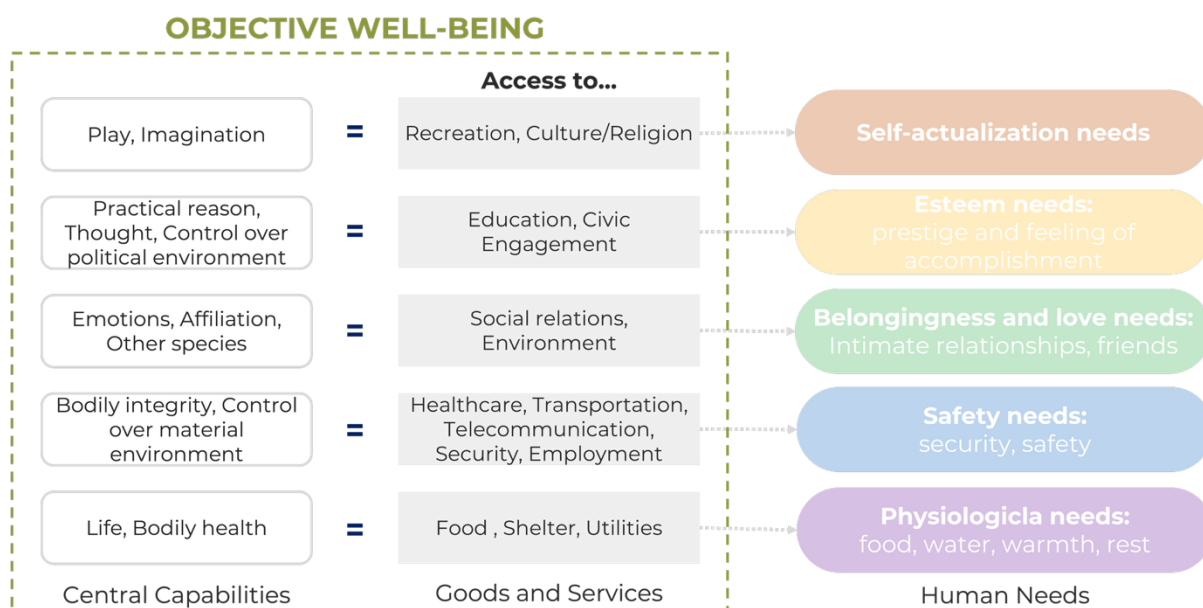


Figure 1: Characterising the relationship between central capabilities, access to goods and services, and the human needs they support

We agree with the Reviewer that an explicit account of the how the model may be operationalised in the context of non-sequential need fulfilment was missing. This has been added to the revised text ([lines 391-402, pages 19-20](#)), as follows:

This means that the scope of the model must be defined and iteratively refined through consultations with community representatives, local experts (and/or, perhaps, individual households). This consultation process is particularly important for calibrating features such as the thresholds for “sufficient” physiological and mobility needs satisfaction that influence involuntary mobility and immobility, the primary and secondary resources (and their substitutes) chosen to support goods and services, conversion factors and the relative importance of needs. These consultations could involve calibration and characterisation using mixed-methods approaches combining deliberative workshops, semi-structured interviews, participatory mapping, and visual methods (e.g., photovoice). The relative importance of non-sequential needs could be quantified using preference elicitation methods such as Analytic Hierarchy Process (Vaidya & Kumar, 2006), Best-Worst Scaling or Discrete Choice Experiments (Potoglou et al., 2011).

Consistent with the literature cited by the Reviewer (i.e., Wahba & Bridwell, 1976), we also explicitly acknowledge that psychological needs only dominate over other needs when they are acutely unsatisfied ([lines 166-168, page 7](#)):

for physiological needs satisfaction at t_x , triggering voluntary or planned mobility (if there is movement capability); an additional natural hazard event occurs at t_r , causing a sudden drop in household objective well-being during mobility; mobility causes household objective well-being to recover back to original (pre-hazard) levels at t_n .

3. Conversion factors are critical to the framework but remain vaguely defined. You mention "intrinsic characteristics" and "socio-political context" but don't provide a systematic taxonomy. For instance, how do you account for legal status (refugee, undocumented, citizen) as a conversion factor that fundamentally alters access to goods/services? How do discriminatory social norms preventing women from accessing transportation or employment get captured? These are not merely "intrinsic characteristics" but products of power structures. The framework would benefit from explicit categorisation of conversion factors and discussion of how structural inequalities are represented.

The Reviewer highlights an important shortcoming in the original manuscript regarding the treatment of conversion factors. We agree that the original text lacked sufficient detail on conversion factors, which we have addressed in the revised manuscript. The updated text in question ([lines 235-250, page 13](#)) includes a taxonomy of conversion factor categories:

For instance, physical and psychological abilities are intrinsic characteristics of household members that act as conversion factors in terms of enabling access to transportation (e.g., driving or using public transit) and telecommunication (e.g., entering a phone or internet contract). Beyond individual traits, societal roles and legal status—such as gender identity, ethnic belonging, or permanent residency—further determine access to these resources, depending on the institutional and normative environment (Robeyns, 2005). The satisfactions of needs, such as those related to sheltering, nourishment, and health, are conversion factors that enable access to employment and education, and facilitate the development of social relations, for instance. We group conversion factors into three categories: personal, institutional, and normative. Their definitions are reported in **Table 5**.

Table 5: Categories of conversion factors

Category name	Definition
Personal	The bodily and mental capacities (e.g., good health, physical ability, or literacy) required to effectively use available resources to satisfy needs.
Institutional	The formal legal rights, entitlements, and regulatory frameworks (e.g., property rights, citizenship/residency status, or conditional permits) that grant or restrict the legitimate use of resources to satisfy needs.
Normative	The informal rules and socially enforced roles (e.g., gender roles, religious beliefs, or cultural identity) that dictate the perceived appropriateness or social permission to use resources to satisfy needs.

The absence of conversion factors—for instance, due to being disabled, socially excluded, legally constrained, poor, or ill—can inhibit one's capabilities to access available primary and secondary resources.

4. **Missing Consideration of Collective Action:** The framework focuses on household-level decisions but many mobility outcomes (especially planned relocation) emerge from collective action, social movements, or government policy rather than individual household optimization. How does the framework incorporate supra-household processes?

We thank the Reviewer for highlighting this important limitation of the framework. Even though the framework does not explicitly capture supra-household processes, it can serve as a useful tool to inform collective action. We outline this point within the explanation of the framework's application to decision-making in the Discussions section (lines 484-490, page 23):

The framework can also guide decisions made outside the household. For instance, individual household modelling results produced by the framework could be aggregated on a community scale and leveraged for developing future urban scenarios (plans) aimed at achieving collective levels of planned or voluntary mobility that local stakeholders consider desirable or acceptable, supporting participatory decision-making around adaptation (Almaden, 2026; Comelli et al., 2024; Cremen et al., 2023; Skidmore & Cohon, 2023).

5. The framework could inadvertently reinforce problematic framings if not carefully implemented. For instance, categorizing some households as lacking "capabilities" for voluntary mobility could justify excluding them from adaptation financing or planned relocation programs ("they lack cultural capital, so relocation won't work"). How do you prevent the framework from naturalizing inequality rather than challenging it? The Discussion mentions participatory stakeholder engagement, but more explicit attention to equity, justice, and power in framework application is needed.

We recognise our oversight in not sufficiently focusing on equity, justice, and power when discussing the application of the framework in practice. We have revised the Discussion section to explicitly address these issues, providing guiding principles for a participatory, equity-oriented application of the framework (lines 495-511, pages 24):

Applications of this framework for policy-making beyond the household scale should adhere to three guiding principles to ensure equitable and just implementation. First, the resources enabling capabilities should not be interpreted as fixed traits of a household, but as factors that can and should be improved through policy. A lack of resources should trigger prioritised institutional support and funding, rather than serve as a justification for exclusion from mobility decisions. Second, there should be representative community participation in identifying the resources and conversion factors that define objective well-being. Mobility outcomes shaped solely by those in power could reinforce structural inequalities; for example, top-down resettlement programs that prioritise safe housing may fragment communities or select sites that prevent the continuation of traditional livelihoods, thereby reducing households' access to goods and services that may be essential to their objective well-being. Third, mobility outcomes produced through application of the framework should be implemented in line with a "Build Back Better" philosophy (Mannakkara & Wilkinson, 2014), striving to ensure that objective well-being after recovery ultimately exceeds pre-hazard levels. Together, these principles ensure that applications of the framework promote "migration with dignity" (McClain et al., 2022), supporting fair and equitable movement that is a proactive path toward better well-being.

6. Empirical Grounding Lacking: The manuscript provides no empirical examples or case studies demonstrating how the framework would classify actual mobility outcomes. Would Hurricane Katrina evacuations be "involuntary" or "voluntary" mobility under this framework? Many households could physically leave (had transportation) but staying was not viable (lacked shelter/utilities). Where do they fall on Figure 3? Worked examples would clarify the framework's analytical utility and reveal ambiguous cases requiring refinement.

The Reviewer's comment regarding the need for empirical grounding is well taken. We agree that empirical examples would enhance the clarity and applicability of the framework. In our framework, Hurricane Katrina evacuations are classified as involuntary mobility because, although some households had the means to leave before the hazard event, remaining in place was not a viable option given the expected threat to life and loss of essential services required to satisfy physiological needs

(i.e., shelter, food, and utilities). To strengthen the empirical grounding, we have added empirical illustrations for each mobility outcome category (lines 82-126, pages 3-5):

Voluntary mobility indicates spontaneous movement away from the place of residence. It often emerges as an adaptive strategy. It can include rural-to-urban migration for accessing improved living conditions and livelihoods. In Bangladesh, for instance, households relocate to urban centres, leveraging rural-urban social networks to escape harsh conditions driven by destructive cyclones and riverbank erosion (McNamara et al., 2016; Uddin, 2024). In India, drought-driven declines in agricultural productivity lead rural residents to seek urban employment (Karutz & Kabisch, 2023). This type of mobility also encompasses movements rooted in pre-existing or culturally embedded practices. In Samoa, families leverage customary land rights and extended family connections to adjust their residences in the face of intensifying storm surges, cyclones, and sea-level rise (Latai-Niusulu et al., 2023). Along the Senegalese coast, fishing communities extend traditional seasonal or circular labour movements in response to sea-level rise, building on long-standing livelihood practices (Zickgraf, 2022). Voluntary mobility also includes shifts in nomadic patterns toward urban settlements, where households can secure basic subsistence amid increasingly unpredictable weather, as observed in Benin, Kenya, and Mongolia (Koutchoro et al., 2025; Tubi & Israeli, 2024; Xu et al., 2021). Voluntary mobility further encompasses decisions to return to original homes following prolonged displacement after major disasters, such as Hurricane Katrina in the United States (Groen & Polivka, 2010) and the Fukushima multi-hazard event in Japan (Murakami et al., 2020).

Planned mobility relates to an organised process in which assistance is provided to move away from the place of residence, and to settle and rebuild lives in a new location (e.g., managed retreat). It typically functions as a coordinated response to existential environmental threats that render locations permanently uninhabitable. For example, state-led planned mobility programs in the Philippines were implemented as a top-down recovery response to the widespread devastation caused by Typhoon Haiyan (Cuaton et al., 2026). In Alaska, community-led planned mobility initiatives serve as a bottom-up response to catastrophic coastal erosion and permafrost melt (Bronen & Chapin, 2013). These initiatives may also operate under a government framework, such as the hybrid relocation frameworks used in Fiji to address rising sea levels (Link et al., 2025; Nichols, 2019).

Involuntary mobility describes forced movement away from the place of residence. It often occurs when immediate safety is compromised. For instance, involuntary mobility occurred after the 2022 Pakistan floods due to building collapse and infrastructure damage (Government of Pakistan, 2022). Persistent food and water insecurity, severe droughts, caused involuntary mobility in Somalia (Wolde et al., 2026). Involuntary mobility also encompasses emergency evacuations that occur during major disasters, like Hurricane Katrina and the Fukushima multi-hazard event.

Involuntary immobility refers to the inability to move from the place of residence. This state of entrapment may result from natural-hazard-induced physical isolation, such is the case in rural Tajik villages where landslides, avalanches, and floods regularly disrupt transport networks (Blondin, 2020). It can also stem from insufficient economic, social, or cultural resources to enable relocation, as experienced by Moroccan youth facing recurring droughts (Van Praag, 2021) and riverbank populations exposed to erosion in Bangladesh (Freihardt, 2025). Involuntary immobility may additionally arise from legal and geographical confinement, as experienced by refugees in Cox's Bazar who face risks from landslides and cyclones within restricted camp boundaries (Rafa, 2026).

7. Resilience Attributes Sequencing Questionable (Table 5, Figure 2): You state resilience capacities are "sequential" with adaptive capacity only engaged after absorptive capacity is exceeded. However, households often employ multiple strategies simultaneously—drawing on savings (economic capital/redundancy) while also rebuilding social networks (resourcefulness) and seeking temporary shelter (redundancy). The sequential model seems overly rigid. Is this a theoretical claim or a modeling simplification? If the latter, acknowledge the limitation.

Thank you for the insightful comment. Our use of a sequential representation of resilience capacities is a theoretical choice grounded in Béné et al. (2012) and Béné, (2013). These works conceptualise absorptive (robustness), adaptive (redundancy), and transformative (resourcefulness) capacities as sequential because they entail progressively higher transaction costs: maintaining a system (i.e., a household's objective well-being) is less costly than adjusting it, which in turn is less costly than fundamentally transforming it. Accordingly, households are expected to prioritise lower-cost responses and engage higher-cost capacities only when lower-cost options prove insufficient following a natural hazard event. Béné, (2013) acknowledges that households may invest in multiple capacities simultaneously, either before or after a hazard occurs; however, these capacities are typically mobilised sequentially in response to the shock itself. We have expanded the text in the manuscript to clarify this theoretical basis for sequential resilience attributes ([lines 308-316, page 16](#)):

Resilience capacities (and their associated attributes) are sequential because they reflect progressively higher transaction costs: maintaining a system (i.e., a household's objective well-being) is less costly than adjusting it, which in turn is less costly than fundamentally transforming it. A household is expected to prioritise lower-cost responses and engage higher-cost capacities only when lower-cost options prove insufficient following a natural hazard event, resorting to its adaptive capacity only after its absorptive capacity is exceeded, and turning to its transformative capacity only when its adaptive capacity is overwhelmed (Béné, 2013; Béné et al., 2012).

It is important to note that the Reviewer's examples align with Béné's theory. Savings are used to regain access to goods and services upon the occurrence of a hazard (i.e., redundancy), but only when existing resources that grant this access are lost or damaged (i.e., robustness is exceeded). Social networks can also be used to restore access to goods and services that have been lost (i.e., redundancy). When the robustness of resources supporting access to physiological needs is exceeded, temporary shelter is sought involuntarily (i.e., redundancy). We also acknowledge that the resilience triangle presented in the manuscript reflects a simplified scenario in which resilience capacities are leveraged simultaneously for all goods and services. In practice, however, different resilience capacities may be mobilised sequentially at different times across goods and services ([lines 319-326, page 16](#)):

The roles of resilience attributes in shaping the resilience triangle for household objective well-being are illustrated in **Figure 2**, for a hypothetical scenario involving a slow-onset hazard event. This event leads to a gradual drop in household objective well-being between t_0 and t_x . Full recovery of objective well-being is then achieved at t_n . The scenario presented in the figure is simplified, implying that the sequential mobilisation of resilience attributes is synchronised across all goods and services underpinning objective well-being. In practice, the mobilisation of a given resilience attribute can occur at different times depending on the good or service involved.

Reviewer #2

This paper presents an ambitious and intellectually engaging framework for conceptualising natural-hazard-induced human mobility through a disaster risk, resilience, and capability-based lens. The integration of objective well-being, household resilience attributes, and mobility outcomes is original and represents a meaningful advance beyond hazard- or infrastructure-centric mobility models. I believe the paper makes a valuable conceptual contribution and should be suitable for publication subject to revisions.

We are grateful to Reviewer 2 for positively evaluating our manuscript, recognising the value of our contribution, and providing constructive feedback, which has helped to significantly improve the manuscript.

That said, I have several comments that I believe would strengthen the manuscript, particularly in relation to its practical applicability and transparency of modelling choices.

1. Practical feasibility and implementation challenges

While the proposed framework is conceptually robust, the manuscript currently underplays the practical challenges associated with operationalising it. In particular, the development of continuous or quantitative functions for vulnerability, conversion factors, social capital, and cultural capital is likely to be highly challenging in real-world applications. Many of the proposed indicators rely on context-specific proxies, qualitative judgements, or data that are difficult to obtain or harmonise across scales.

We thank the Reviewer for these helpful comments. We acknowledge that the original discussion on operationalising the framework was too brief. The revised manuscript provides a much more detailed explanation of the framework's practical implementation, including the associated challenges. Below, we describe the associated improvements in more detail.

I recommend that the authors more explicitly acknowledge these challenges in the Discussion, including:

Data availability and quality constraints

We explicitly acknowledge limitations in the quality and nature of global datasets related to primary resources, including concerns regarding accuracy and uncertainty (lines 408-418, page 20):

These databases typically provide aggregated information on the presence of primary resources, often fail to capture key dimensions of service access, such as quality of provision, and may be incomplete or biased (e.g., underrepresenting informal settlements). They should be disaggregated, where relevant, and supplemented with local population microdata (e.g., Office for National Statistics, 2020; Ruggles et al., 2025; World Bank Jobs Group, n.d.) and human activity-based data from travel survey information to produce detailed synthetic household-level datasets that capture individual people and their dynamic dependencies on primary resources (see Menteşe et al., 2023 for more details). The accuracy of the resulting datasets can be assessed through local (household-level) surveys, where feasible. Uncertainties can be appraised through appropriate sensitivity or scenario analyses.

Furthermore, we emphasise the intrinsic difficulty of measuring secondary resources and the resulting need to develop appropriate corresponding proxy indicators in many cases (lines 422-440, pages 21-22):

Secondary resources are largely intangible and generally harder to quantify than primary resources. They can be directly measured through localised surveys on income or consumption (i.e., economic capital; Deaton, 2019; Meyer & Sullivan, 2003), networks of social relations (i.e., social capital; Moghfeli et al., 2023; Saint Ville et al., 2016), and cultural activities, possessions, and education (i.e., cultural capital; Balboni et al., 2019; Kraaykamp & Van Eijck, 2010; Sieben & Lechner, 2019; Sullivan, 2001). When such direct measurement data are not available (as is often the case), quantification of relevant secondary resources can be based on proxies tied to household-level characteristics and primary resources that sustain earnings, social relations, and culture. Composite indices constructed from information on asset ownership, household structural features (i.e., walls, roof, and floor materials), and the presence of utility infrastructure are widely used as proxies for economic capital (Filmer & Scott, 2012; Lovaton Davila et al., 2022; Varghese et al., 2021). Social capital can be measured in terms of demographic homogeneity (bonding social capital; Kyne & Aldrich, 2020), walkability, and access to social infrastructure and telecommunication (bridging social capital; e.g., Cabrera & Najarian, 2015; Fraser et al., 2024; Mazumdar et al., 2018; Williams & Hipp, 2019). Cultural infrastructure can be used to measure cultural capital; previous studies have demonstrated this using the density of culturally significant sites to estimate intangible heritage (embodied capital; Brandano et al., 2025) and the concentration of high-skilled individuals to proxy institutionalised capital (Backman & Nilsson, 2018).

Contextual variability and transferability issues

We have clarified that proxies for resources and associated conversion factors are context-specific (lines 443-446, page 22):

The definitions of primary resources supporting access to goods and services, secondary resources proxies, as well as relevant conversion factors, are inherently context-specific. They should be developed based on appropriate ethnographic literature and/or through consultation with local stakeholders.

We also acknowledge the transferability challenges associated with the framework's transferability. The following lines have been added to a new Limitations subsection (lines 546-547, page 25):

Finally, the framework's general transferability is limited by its reliance on context-specific measurements and definitions.

The role of expert judgement and stakeholder engagement in parameterisation

To address this comment, we explicitly note the important role of expert judgement and stakeholder engagement in characterising the components of the framework (lines 391-402, pages 19-20):

This means that the scope of the model must be defined and iteratively refined through consultations with community representatives, local experts (and/or, perhaps, individual households). This consultation process is particularly important for calibrating features such as the thresholds for "sufficient" physiological and mobility needs satisfaction that influence involuntary mobility and immobility, the primary and secondary resources (and their substitutes) chosen to support goods and services, conversion factors and the relative importance of needs. These consultations could involve calibration and characterisation using mixed-methods approaches combining deliberative workshops, semi-structured interviews, participatory mapping, and visual methods (e.g., photovoice). The relative importance of non-sequential needs could be quantified using preference elicitation methods such as Analytic Hierarchy Process (Vaidya & Kumar, 2006), Best-Worst Scaling or Discrete Choice Experiments (Potoglou et al., 2011).

The implications of uncertainty and partial observability for model outputs

We have included a discussion of uncertainty in the Limitations subsection (lines 531-542, page 25):

First, mobility outcomes derived from the framework are inevitably uncertain. Some uncertainty is quantifiable (e.g., measurement error in proxies; probabilistic hazard-induced damage via vulnerability functions) and can be propagated through the model using Monte Carlo or ensemble approaches to produce probability distributions of mobility outcomes. Other uncertainty is epistemic or deep (e.g., unobserved aspects of secondary resources) and is not readily reduced to a single probability distribution (Cox, 2012; Walker et al., 2013). This uncertainty can be explored by drawing on insights from stakeholder consultations to define multiple, plausible sets of modelling inputs corresponding to unobservable or epistemically/deeply uncertain parameters. Mobility outcome results could then be presented as ranges or scenario envelopes, rather than single best-estimate predictions, and communicated clearly to stakeholders alongside the underlying assumptions.

This would help avoid an impression of false precision and clarify that the framework is a guiding structure rather than a fully operational model at this stage.

While the original manuscript noted that the framework is intended as an initial conceptual step toward a full-fledged modelling methodology, we have further emphasised this point at the beginning of the Limitations subsection ([lines 529-531, page 25](#)):

The framework is proposed as a conceptual guide for future modelling rather than a fully implementable tool. As such, there are a number of potential challenges associated with operationalising the framework that warrant further exploration.

2. Rationale for parameter and indicator selection

Several tables (notably those mapping goods and services, resources, and forms of capital) present parameter choices without sufficient justification. It is not always clear why certain parameters were selected, whether the lists are intended to be exhaustive or illustrative, or how alternative formulations might affect outcomes.

We thank the Reviewer for pointing out this limitation of the original manuscript. We clarify the rationale behind parameter choices in the revised manuscript. We now expand on this clarification in our responses to the Reviewer's more specific comments.

The paper would benefit from:

A clearer explanation of the principles guiding parameter inclusion and exclusion

We respond to the comment by outlining in the revised manuscript how:

- (1) The particular goods and services included were selected ([lines 178-183, page 7](#)):

Leveraging existing work on well-being indexes (European Social Survey, n.d.; Morshedi et al., 2024; OECD, n.d.; Office for National Statistics, 2026; University of Waterloo, n.d.), we propose to quantify objective well-being in terms of access to a number of goods and services (see **Table 2**) that support the satisfaction of human needs (see **Figure 1**). We select goods and services based on the indicators used in these well-being indexes that are not derived from respondents' subjective evaluations (i.e., indicators of subjective well-being).

- (2) The primary and secondary resources included were selected ([lines 213-218, page 10](#)):

We map primary and secondary resources to the corresponding goods and services supported in line with Wang et al. (2024), where relevant; see **Table 4**, which also provides the associated needs and central capabilities. The primary resources selected to provide access to each good or service are those that typically underpin their provision in a given context, assuming all relevant infrastructure is present and functioning. All categories of secondary resources are deemed to provide access to goods and services.

Explicit acknowledgment that alternative parameterisations are possible

We agree with this observation and now explicitly acknowledge it in the manuscript. The list of goods and services provided is designed to be exhaustive, in line with the objective well-being indexes reviewed. We provide relevant examples of different possible selections of resources ([lines 218-228, page 10](#)):

The specific mix of goods, services, and underlying resources varies depending on the level of infrastructural development and the way governance is structured in a given context. In contexts where formal utility infrastructure is limited or absent—such as in parts of sub-Saharan Africa—provision of goods and services often relies directly on human labour (frequently that of women and children) and natural resources, including forests and water sources (Graham et al., 2016; Lambon-Quayefio, 2024). In contexts where governance structures favour the commodification of goods and

services (including education and healthcare) over their public provision, their access may depend on economic capital. In contexts where informal governance dominates, access to essential goods and services may depend heavily on social and cultural capital (Helmke & Levitsky, 2004).

A brief discussion of how weighting, aggregation, or prioritisation might be handled in practice

We appreciate this comment. These issues are addressed in sections of the manuscript that were originally developed in response to Reviewer 1. Specifically, aggregation is illustrated in the section discussing how the framework can be used to guide regional policy making (lines 484-490, page 23):

The framework can also guide decisions made outside the household. For instance, individual household modelling results produced by the framework could be aggregated on a community scale and leveraged for developing future urban scenarios (plans) aimed at achieving collective levels of planned or voluntary mobility that local stakeholders consider desirable or acceptable, supporting participatory decision-making around adaptation (Almaden, 2026; Comelli et al., 2024; Cremen et al., 2023; Skidmore & Cohon, 2023).

While prioritisation (and weighting) is discussed in the context of engagement with local stakeholders (lines 391-402, pages 19-20):

This means that the scope of the model must be defined and iteratively refined through consultations with community representatives, local experts (and/or, perhaps, individual households). This consultation process is particularly important for calibrating features such as the thresholds for “sufficient” physiological and mobility needs satisfaction that influence involuntary mobility and immobility, the primary and secondary resources (and their substitutes) chosen to support goods and services, conversion factors and the relative importance of needs. These consultations could involve calibration and characterisation using mixed-methods approaches combining deliberative workshops, semi-structured interviews, participatory mapping, and visual methods (e.g., photovoice). The relative importance of non-sequential needs could be quantified using preference elicitation methods such as Analytic Hierarchy Process (Vaidya & Kumar, 2006), Best-Worst Scaling or Discrete Choice Experiments (Potoglou et al., 2011).

3. Clarifying the conceptual vs operational scope

At times, the manuscript appears to move close to proposing an implementable modelling system, while remaining primarily conceptual. I suggest the authors clarify the intended scope of the contribution, for example by:

Explicitly positioning the framework as a conceptual scaffold to inform future modelling efforts

We thank the Reviewer for their helpful comment. The manuscript is designed as a Perspective paper that deliberately provides a conceptual overview rather than a fully implementable modelling system. To make this clearer, we have added a statement at the beginning of the Limitations subsection clarifying that the framework should be understood as a conceptual guide for future modelling rather than a fully operationalisable tool (lines 529-531, page 25):

The framework is proposed as a conceptual guide for future modelling rather than a fully implementable tool. As such, there are a number of potential challenges associated with operationalising the framework that warrant further exploration.

Distinguishing clearly between components that are well-established in practice (e.g., physical fragility modelling) and those that remain methodologically emergent (e.g., cultural capital and aspiration dynamics)

Thank you for this comment. We have modified some text in the Vulnerability paragraph to better clarify this distinction. The revised lines read as follows (lines 447-449, page 22):

Vulnerability (robustness) of primary resources can be captured using well-established engineering-based fragility models that express physical damage in terms of hazard intensity (Gentile et al., 2022).

And (lines 461-464, pages 22-23):

Similarly, new models are emerging to convert damage to primary resources supporting employment, social relations, and culture into losses of secondary resources, such as economic capital (see Markhvida et al., 2020; Verschuur et al., 2020).

Additionally, we acknowledge that methods (e.g., proxies) to measure secondary resources are emergent, as highlighted in the Exposure paragraph of the manuscript (lines 422-440, pages 21-22):

Secondary resources are largely intangible and generally harder to quantify than primary resources. They can be directly measured through localised surveys on income or consumption (i.e., economic capital; Deaton, 2019; Meyer & Sullivan, 2003), networks of social relations (i.e., social capital; Moghfeli et al., 2023; Saint Ville et al., 2016), and cultural activities, possessions, and education (i.e., cultural capital; Balboni et al., 2019; Kraaykamp & Van Eijck, 2010; Sieben & Lechner, 2019; Sullivan, 2001). When such direct measurement data are not available (as is often the case), quantification of relevant secondary resources can be based on proxies tied to household-level characteristics and primary resources that sustain earnings, social relations, and culture. Composite indices constructed from information on asset ownership, household structural features (i.e., walls, roof, and floor materials), and the presence of utility infrastructure are widely used as proxies for economic capital (Filmer & Scott, 2012; Lovaton Davila et al., 2022; Varghese et al., 2021). Social capital can be measured in terms of demographic homogeneity (bonding social capital; Kyne & Aldrich, 2020), walkability, and access to social infrastructure and telecommunication (bridging social capital; e.g., Cabrera & Najarian, 2015; Fraser et al., 2024; Mazumdar et al., 2018; Williams & Hipp, 2019). Cultural infrastructure can be used to measure cultural capital; previous studies have demonstrated this using the density of culturally significant sites to estimate intangible heritage (embodied capital; Brandano et al., 2025) and the concentration of high-skilled individuals to proxy institutionalised capital (Backman & Nilsson, 2018).

Reviewer #4

Summary:

This Perspective proposes a framework for evaluating natural-hazard-induced human mobility via household objective well-being loss and recovery, using disaster risk and resilience concepts. The manuscript is very well written, clearly structured, and provides a comprehensive conceptual synthesis. I find the framework valuable and the implementation discussion helpful. I recommend acceptance after minor revisions, focused on feasibility/limitations and sharper positioning of novelty.

We are grateful to Reviewer 4 for their positive assessment of our manuscript and for recognising the value of the proposed framework. Their comments have helped to significantly strengthen the manuscript. We address each of their points in detail below.

Main comments:

1. Feasibility, limitations, and prioritisation for implementation

While the framework is comprehensive, it currently reads as difficult to operationalise in practice. Even with context-specific tailoring, boundaries between concepts (e.g., goods/services vs resources; conversion factors vs secondary capital; vulnerability vs “loss of conversion factors”) may blur in real

applications, and key inputs will often be missing. This implies many normative modelling choices and additional uncertainty, potentially limiting uptake.

The reviewers' constructive feedback on the framework's feasibility, limitations, and real-world applicability has been carefully considered. We now describe how this feedback has been addressed through our responses to the Reviewer's more specific comments.

I suggest the authors add:

- A limitations subsection discussing (i) data sparsity/measurement error; (ii) normative choices (e.g., thresholds for "physiological" and "movement" needs; weighting of goods/services; defining redundancy/substitutes); (iii) potential double counting/endogeneity (e.g., feedbacks between capitals and access to goods/services); and (iv) transferability limits across contexts.

We thank the Reviewer for this helpful suggestion. We have added a dedicated Limitations subsection addressing each of the points raised by the Reviewer in this comment (lines 529-547, page 25):

The framework is proposed as a conceptual guide for future modelling rather than a fully implementable tool. As such, there are a number of potential challenges associated with operationalising the framework that warrant further exploration. First, mobility outcomes derived from the framework are inevitably uncertain. Some uncertainty is quantifiable (e.g., measurement error in proxies; probabilistic hazard-induced damage via vulnerability functions) and can be propagated through the model using Monte Carlo or ensemble approaches to produce probability distributions of mobility outcomes. Other uncertainty is epistemic or deep (e.g., unobserved aspects of secondary resources) and is not readily reduced to a single probability distribution (Cox, 2012; Walker et al., 2013). This uncertainty can be explored by drawing on insights from stakeholder consultations to define multiple, plausible sets of modelling inputs corresponding to unobservable or epistemically/deeply uncertain parameters. Mobility outcome results could then be presented as ranges or scenario envelopes, rather than single best-estimate predictions, and communicated clearly to stakeholders alongside the underlying assumptions. Second, secondary resources are often interdependent and mutually convertible, and their development frequently depends on both primary resources and other secondary resources. Because of this, it is difficult to treat secondary resources as discrete entities, and there is a risk of double-counting them in empirical applications. Finally, the framework's general transferability is limited by its reliance on context-specific measurements and definitions.

- A brief "minimum viable implementation" roadmap, e.g., a tiered approach that starts from a small set of measurable, near-universal indicators (food, shelter, utilities, transport/telecom, healthcare, security, livelihood) and then adds social/cultural dimensions and conversion factors as data allow.

To address this comment, we have added a paragraph describing a minimum viable implementation of the framework. We explain how the framework can be implemented using only secondary data when stakeholder engagement is not feasible, with the aim of assessing its applicability and the quality and availability of existing data, rather than directly informing policy development. We emphasise that incorporating secondary resources is critical for the framework's practical application, as these capture important intangible determinants of household risk and resilience (a key contribution of our framework) (lines 512-527, pages 24-25):

A minimum viable implementation of the framework is still possible in settings where local stakeholder engagement is limited or impractical and where secondary-resource surveys are lacking, as long as data on primary resources are available. This approach can support preliminary analyses to test framework applicability, identify data gaps, and assess data quality; however, it should not inform inference or decision-making unless validated with local stakeholders in line with the guiding equity-oriented principles outlined above. For this type of implementation, relevant secondary resources and conversion factors can be identified through appropriate ethnographic literature (e.g., Dayley, 2009;

Howard, 2018; Hyler, 2013; Mikkonen, 2017; Mukil et al., 2026; Thurnell-Read, 2021). Social and cultural infrastructure can then be mapped using digital platforms that capture user-generated place-based activity data (e.g., Google Places, Flickr, Foursquare Places). On this basis, households within a given building can be assigned an approximate level of objective well-being derived from their infrastructural environment and proximity to social and cultural sites. The prioritisation of needs can be approximated using Maslow's hierarchy if empirical evidence demonstrates its relevance to the context (i.e., the setting is Western). Otherwise, physiological and movement needs should at least be examined and can be considered to have equal priority.

2. Discussion of exposure data and household-level granularity

The compiled list of global exposure datasets is useful; however, many global products are not designed for household-level assessment and may be too coarse, incomplete, or biased (particularly for informal settlements, service quality, network functionality, and within-city inequalities). The manuscript notes that local data can supplement global sources, but I think a stronger caution is warranted. I suggest clarifying what "household-level" means in practice (microdata vs synthetic households vs gridded proxies), what global datasets can and cannot reliably represent (asset presence vs actual service access/quality), and how resulting bias/uncertainty will be treated (e.g., sensitivity/scenario analyses and validation with local surveys).

We appreciate the Reviewer's comment regarding the quality, use, and limitations of global datasets when operationalising our framework. This feedback was very helpful in refining the Exposure paragraph of our manuscript, which now reads as follows (lines 408-418, page 20):

These databases typically provide aggregated information on the presence of primary resources, often fail to capture key dimensions of service access, such as quality of provision, and may be incomplete or biased (e.g., underrepresenting informal settlements). They should be disaggregated, where relevant, and supplemented with local population microdata (e.g., Office for National Statistics, 2020; Ruggles et al., 2025; World Bank Jobs Group, n.d.) and human activity-based data from travel survey information to produce detailed synthetic household-level datasets that capture individual people and their dynamic dependencies on primary resources (see Menteşe et al., 2023 for more details). The accuracy of the resulting datasets can be assessed through local (household-level) surveys, where feasible. Uncertainties can be appraised through appropriate sensitivity or scenario analyses.

3. Capability-based approach section

The capability-based section is clear, but it is not obvious to me whether it is intended primarily as a well-executed conceptual background summary or as an original contribution that synthesises and structures these concepts for modelling; a brief signposting sentence at the start clarifying this would help.

We now clarify that the purpose of this section is to facilitate modelling (rather than act as a conceptual background summary). The first sentence of this section (lines 143-145, page 6) now reads as:

To effectively synthesise and model well-being as capabilities, we interpret Nussbaum (2003)'s functionings as the essential needs outlined in Maslow's (1943) theory of human motivation (e.g., Clark et al., 2018; Tseng & Stojadinović, 2024).

4. Minor comments/Literature:

IDMC displacement risk modelling: Since the introduction cites IDMC displacement figures, the authors may also wish to reference IDMC's displacement risk modelling work (e.g., Global disaster displacement risk: a baseline for future work: <https://www.internal-displacement.org/publications/global-disaster-displacement-risk-a-baseline-for-future-work/>) and

related recent developments (e.g., Meiler et al., 2025: <https://iopscience.iop.org/article/10.1088/2752-5295/ae014c>), positioning these alongside approaches that primarily model direct hazard–displacement relationships.

We thank the Reviewer for this relevant recommendation. The Meiler et al. (2025) paper mentioned by the Reviewer, which is referenced as the methodological basis for the Global Displacement Risk Model on the IDMC website, is cited in the revised version of the manuscript (lines 44-47, page 2) as follows:

Many of these models continue to rely on a simplistic cause-and-effect paradigm, assuming observed *involuntary* mobility arises solely as a direct consequence of natural hazard events (e.g., Chen & Caldeira, 2020; De Lellis et al., 2021; Kam et al., 2024; Meiler et al., 2025; Schwaller et al., 2024; Smirnov et al., 2023).

Mixed Migration Centre / 4Mi: MMC’s 4Mi dataset could be a useful illustrative example of local, multi-driver data aligned with the framework’s household-level ambition: <https://mixedmigration.org/4mi/>

We thank the Reviewer for highlighting this valuable resource. The dataset could serve as a useful validation tool in the future, as it expands with additional observations and more granular information on migrants’ locations of origin and the specific hazards to which they were exposed becomes available.

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