

Author Response to Referee #1 (RC1)

Dear Referee #1,

We are profoundly grateful for your exceptionally insightful and constructive review. Your deep understanding of the conceptual nuances within the DMDU field has been invaluable. We sincerely appreciate your recognition of our study's significance and your guidance in refining its theoretical foundations. We have thoroughly addressed every point you raised. The most significant revisions concern the conceptual framing of 'robustness' and 'adaptiveness' to eliminate the false dichotomy you identified. We have also carefully incorporated all minor editorial suggestions. Below, please find our point-by-point response. All changes in the manuscript have been highlighted using the 'Track Changes' feature for your convenience.

Comment 1 (Conceptual):

RC1: *"The term robustness, as indicated in my initial review comments, is much abused in the sense that different fields use it differently. There is, of course, the concept of a robust statistics. In engineering, a structure is made robust by designing it for some multiple of the strain that might be incurred during its lifetime. The meaning of robustness as applied to the problem of decision making under deep uncertainty has from the onset been similar to that used by the authors: "the ability of a strategy [sic] to maintain acceptable performance across a wide range of plausible futures" (l. 135-6). The use of the word "strategy" is itself somewhat problematic. A more apt phrase would be "course of action". That is because it is in the essence of robust decision approaches in the DMDU setting to use adaptation as the principal mechanism for determining what will unfold as a course of action. What is established as a result of a robust decision analysis is not so much a strategy in the traditionally understood meaning of the term but rather a set of rules that may be agreed to ex ante the better to guide the adaptations that the principles of robustness under deep uncertainty presume will be necessary."*

Response: We agree with your observation that the relationship between robustness and adaptiveness in decision-making under deep uncertainty (DMDU) should be more clearly delineated. We have reframed this discussion to avoid pitting "robustness" against "adaptiveness. We believe this change helps better capture the evolving nature of flood management decisions in the context of uncertainty. To resolve this, we have implemented a

revision throughout the manuscript:

Line 135-136 (Page 6), We changed the text from “we define ‘robustness’ as the ability of a strategy to maintain acceptable performance across a wide range of plausible futures” to “we define ‘robustness’ as the ability of a **course of action** to maintain acceptable performance across a wide range of plausible futures.”

Lines 526-532 (Page 27-28), Section 4.3, “The robustness-focused analysis... whereas the adaptiveness-focused analysis... These differing outcomes demonstrate why it is crucial to evaluate multiple criteria together.” Is changed to “An analysis focused solely on static performance metrics (e.g., ARRR and BCR) would rank options like Tun50 and Tun70 as the top performers. In contrast, an analysis that also incorporates adaptive characteristics (effectiveness period and flexibility) reveals the advantages of a pathway like D+G+Tun30. These differing outcomes demonstrate why moving beyond a single-metric assessment to a multi-criteria evaluation is crucial for identifying strategies that are robust over the long term.”

RC1: *“Robust Decision Making (RDM), to which the authors specifically refer, is built upon principles derived from traditional decision science, exploratory modeling (Bankes, 1993), Assumption Based Planning (Dewar, 2002), and an operationalized version of scenario planning. What the authors cite as “metrics...to quantify robustness under uncertainty” (l. 251-2) represent only the first of these components. They can be used as metrics, as the authors later do, but they were not proposed by their creators as definitions of robustness as the authors also do. They are a set of theoretically derived alternative decision rules. It is precisely because all recognize that they are susceptible to perverse corner solutions, particularly under evolving circumstances, that they cannot in themselves be guaranteed to provide robustness nor easily to account for all the multi-attribute problems of wicked problems under deep uncertainty. They work best in a world in which there are only a limited number of criteria for success. It was precisely for this reason that a more over-arching concept of robustness was required and methodologies developed to explore robustness. And those methods are inherently adaptive in pursuit of robustness. (As an historical aside, what is termed RDM was originally called Robust Adaptive Planning (RAP). RDM was presented as a larger categorical term to which RAP belonged. The further vicissitudes of this nomenclature are not relevant to this review.)1”*

Response: We have revised the introduction and methodology to clarify that the decision metrics (e.g., Laplace) are used as initial filters to identify candidate strategies based on a specific performance criterion (now termed "sufficiency"). We then explicitly state that the subsequent adaptive pathways analysis is the mechanism that ensures long-term "resilience" (another term we have incorporated) and "robustness" by allowing the strategy to evolve,

thereby avoiding the "perverse corner solutions" associated with rigid adherence to a single decision rule.

Line 251-252 (Page 9), Section 2.2. “Various metrics can be used to quantify robustness under uncertainty...” is changed to “Various metrics can be used to evaluate course of actions’ performance under uncertainty and identify those that are sufficient against a given criterion quantify robustness under uncertainty including Maximax, Maximin, Mean-variance, Starr’s domain criterion, Laplace’s principle of insufficient reason, etc. (Molina-Perez et al., 2019)”

Line 260-4 (Page 9), Section 2.2, we add “It is important to note that while metrics like Laplace’s principle provide a useful initial screening for sufficient strategies, they can be prone to corner solutions and may not fully capture multi-attribute challenges under deep uncertainty. The subsequent adaptive pathways analysis (DAPP) is therefore essential to complement this initial screening and build a resilient long-term strategy.”

To demonstrate this, we also add a reference as you suggested:

Molina-Perez, E., Groves, D.G, Popper, S.W et al. (2019). Developing a robust water strategy for monterrey, Mexico: diversification and adaptation for coping with climate, economic, and technological uncertainties. Rand Corporation.

RC1: “Again, this matters because despite offering a workable definition of robustness, their actual use of the concept still sets up what is in the opinion of the review a false dichotomy with adaptiveness: e.g., “...comparing the costs and benefits of a flexible investment strategy with those of a less flexible, that is, a more robust strategy” [emphasis added, l. 330]. This usage tends much more toward the engineering use of the term than that which has evolved in the DMDU community.”

Response: The problematic phrasing you cited (e.g., L. 330) has been completely removed and reworded. The framework is now presented not as a trade-off between robustness and adaptiveness, but as a sequential process: *identify sufficient starting points -> enhance their long-term robustness through adaptive planning.*

Line 330 (Page 11). “Comparing the costs and benefits of a flexible investment strategy with those of a less flexible, that is, a more robust strategy” is changed to “One way of assessing the value of flexibility is thus by comparing a flexible investment strategy against a strategy that scores highly on a static sufficiency metric but offers fewer future options.”

RC1: “Let’s take this last point as a step towards resolution. If there is fundamentally a concept of system integrity lying behind the use of these theoretical decision rules as metrics, let’s use

a term better suited to the characterization of an evolving system than to that of a strategy or course of action. Since they are being used in the sense of achieving criteria for measuring system integrity with regards to pluvial flood risk, perhaps two terms that would avoid the problems that currently arise in the draft would be to characterize these as measures of “sufficiency” or “resilience”. Both would be more apt in characterizing long-term fault resistance by a system built over time than is the word “robust” which is used to characterize a course of action determined by analytically derived decision rules.”

Response: We appreciate your suggestion to consider "resilience" or "sufficiency" as more appropriate terms for assessing system integrity in long-term planning. We have adopted these terms in the manuscript to characterize the system's ability to withstand and adapt to varying flood risks over time (e.g. Line 253; Line 535). This change aligns better with the conceptual framework and ensures that our approach remains consistent with DMDU methodologies.

Line 406-408 (Page 20), Section 3.2. we revise the sentence: The robustness analysis serves as the foundation of our methodology, ensuring that the proposed solutions can withstand future uncertainties”. to “The robustness analysis serves as the foundation of our methodology, ensuring that the proposed options can meeting the sufficiency criteria under future uncertainties”.

Minor revision

Comment 1: The sentence in l. 23-24 is problematic as it stands. Suggest: “Decision-makers face significant challenges in determining whether and how to invest in flood defence.”

Response: We have revised the sentence as suggested.

- Change made: Page 1, Line 23: The sentence now reads: “Decision-makers face significant challenges in determining whether and how to invest in flood defence.”

Comment 2: Lines 24-25. This sentence lays the fundamental problem focused on by this reviewer squarely up front. Despite that, both instances of the word “to” should be deleted.

Response: Accepted. We have deleted the two instances of "to".

- Change made: Page 1, Line 24: The sentence has been corrected.

Comment 3: Line 125. Delete “an” before “options”.

Response: Accepted. The article "an" has been deleted.

- Change made: Page 4, Line 125: Corrected to "...generating candidate adaptation options...".

Comment 4: Lines 310-11. The phrase “vulnerable scenarios” does not quite ring correctly. It is not the scenarios which are vulnerable. Rather, these are scenarios under which particular chosen courses of action may prove to be vulnerable. It might be better instead to refer to “stressful” scenarios.

Response: As per your comment, we have replaced the phrase "vulnerable scenarios" with "stressful scenarios" to clarify that these are scenarios in which certain adaptation strategies may be tested beyond their capacity to meet long-term objectives. This revision enhances the precision of our language and reflects a more accurate understanding of the scenarios in question.

- Change made: Line 310-311 & Line 281: We replaced "vulnerable scenarios" with "stressful scenarios" as noted above.

After these revisions, we double-check the entire manuscript to make sure no new errors were introduced and that the text reads smoothly for an international audience. We are confident that with these extensive language corrections, the manuscript’s readability greatly improves. Once again, we thank Referee #1 for their valuable insights and careful review. The feedback on both the conceptual framing and the writing has been extremely helpful. We implement all the above changes in the revised manuscript. We appreciate the reviewer’s positive comments about our study’s merit, and we are committed to improving the manuscript accordingly. Thank you for helping us strengthen this work.