Re: RC2 – Comment on NHESS-2021-144, Anonymous Referee #2 (06 Aug 2021)

Comment: The manuscript presents a MCA analysis of different flood mitigation options for a complex basin in Texas, USA. Topic is interesting and fits the scope of the journal. The idea itself is (obviously) not new in the literature, nor relevant methodological issues are here developed, but the case study is interesting and potentially deserves for publication, once a series of points are modified and/or clarified.

Response: While we appreciate the reviewer's familiarity with MCDA approaches within the academic literature, we similarly acknowledge that such concepts are not employed in-practice within large-scale reservoir planning and mitigation studies, as demonstrated in this article (also see https://www.nwo.usace.army.mil/Missions/Civil-Works/Planning/Planning-Projects/Cherry-Creek-DSMS/, https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/17692). Instead, a qualitative description of environmental and societal risks is included in dam planning studies, while the ranking of alternatives during the preliminary planning phase is conducted with cost-benefit analyses based on extent of flood inundation and capital costs. Our goal with this study was not to present a case study to show how MCDA is used but to demonstrate how current practical planning paradigms could be improved with geospatial datasets and overlays in a manner that is intuitive and able to be streamlined into standard modeling approaches (e.g., HEC-HMS/HEC-RAS are the most commonly used programs in the United States for studying hydrology and flood inundation) by combining CBA with MCDA. The integration of CBA with MCDA is novel within the dam planning literature, as most academic studies that used methods from MCDA have focused on reservoir operations optimization and not large-scale planning. This novelty has been further explained and highlighted in the revised Manuscript, Lines 90-99, with additional background literature for support. Here, we have also further identified the novelty of this study that incorporates inter-disciplinary social and environmental considerations within water resources management MCDA approaches for dams, rather than being limited to flood characteristics.

We also realize this consideration is constantly evolving and differs between geographic locations. We intended for this statement to recognize the discrepancy between studies and widespread practice with an encouragement toward explicit quantification of, and therefore integrated consideration of, social/environmental factors within dam mitigation frameworks.

Major Points:

Equation (1) – Composite Risk

Factors R (Environmental, Social) are weighted averages of evaluation scores. Concept is clear, but we have no information on how such scores are given, we only know about their general meaning (sources of contaminants, soil erodibility, medical facilities…). Lines 256-261 provide a long list of items to be considered in the risk evaluation. However, it is not clear which of them has been really considered in the environmental and social criteria, and how.

Response: Reference response to comment below for Section 3.2.3.

In different words: what do factors "e_j" exactly represent? Are they binary quantities (e.g.: presence of a source of contaminant in a cell), extensive quantities (e.g.: length of inundated road in a cell), intensive quantities (percentage of flood insurances among residents)? How the scoring 0-100 is attributed to each factor for each cell? Do cells have a uniform extension?

Response: Updated. Reference discussion in Lines 258-272.

In particular "Stream samples were obtained from field campaigns following Hurricane Harvey, which were used in this study to validate the areas of environmental burdens associated with contamination in local waterways." I have not understood how such data were used to define values for the environmental factors in each cell.

Response: Language updated for clarity in Lines 298-300.

Finally, I strongly suggest providing a short description of the SoVI (Social Vulnerability Index) and variables involved in the index.

Response: Added, Lines 303-306.

Equation (2) – Impact Functions

1) What are the "zonal statistics for the composite risk and the modeled inundation area of each alternative"?

Response: Clarity added that this is an ArcGIS command, Line 281.

2) What are the "zones"? the inundated areas for each scenario? I understand that "a_i" are the corresponding inundated surfaces, is this correct? Or do they also comprehend the areas impacted by the "ancillary risk" (see below)?

Response: Clarity added in Line 284.

3) What is the summation index in equation (2)?

At the end of the story, I cannot understand IF. If "Rbar" is an average (I guess, spatial average) over the zone and "a" is the area of the zone, than Rbar is constant over the zone and IF=Rbar+ancillary risk. But this has no sense, therefore I conclude that I was not able to understand equation (2).

Response: IF represents a composite "Impact Factor" for environmental or societal considerations within the watershed of interest.

Yes, Rbar is a spatial average of each zone, clarified in Lines 283-284.

Ancillary impact was calculated similarly to the composite risk calculation and added, per Eqn. 3. For example, let's look at the Environmental Impact Factor (IF_E) for Alternative A2 (Enlarged Receiving Channel). Here, our Zonal average of the environmental risk raster (see Fig. 4a) under the modeled inundation bound for this alternative (see Fig. 5b) equaled 68.12 (for an inundation area of 382.8 he). Then, we assigned a negative environmental impact of 100 (the worst score possible) for this alternative, due to its impact on the highly-threatened wildlife here (in a hypothetical stakeholder situation, one might definitely argue this risk is not "that important", and that group of decision-makers would then have to explain to the ecosystem protection persons why this risk value should be reduced, but as it stands in current planning, while the Alligator snapping turtle may be noted by the USACE in their reports, this consideration is not explicitly included within the modeling paradigm as a value that can be assigned a number and incorporated into the ranking framework). In assigning this easement area (which was calculated to be 259.99 he in GIS) a risk/impact of 100, we can perform a simple weighting calculation as such:

$$IF_E = \frac{(68.12 * 382.8he + 100 * 259.99he)}{(382.8he + 259.99he)} = 81.01\ (as\ shown\ in\ Table\ 4)$$

Additional clarification has been added to Eqn. 3 and Lines 283-287, 330-337.

<u>Section 3.2.2 - Ancillary Risk</u>

I see conceptual inconsistencies here. Soil use / buyouts due to mitigation measures are not risks, are deterministic impacts; they have 100% probability along the lifetime of the mitigation measure, and they last for all such time. On the other hand, the damage from a flood scenario has a probability of exceedance less than 100% in the given period. What is here called "ancillary risk" is not a risk at all and should not simply be added to the flood risk by assigning certain values of R-scoring for the areas impacted by the measures, as here done.

On the other hand, the extra-flooding expected along the Cypress Creek is an additional/ancillary risk, and it is correct to handle it as such. Why is such area simply accounted by a R_S=100 scoring? It should be added to the flooded area and evaluated with respect to CB and IFs.

Response: Language for ancillary "risks" updated to state ancillary "impacts" throughout manuscript.

The additional flooding along Cypress Creek will remain "ancillary" for purposes of demonstrating our proposed framework, as we aim to keep the three primary domains distinct within the first round of MCDA (environmental and social risks in the area overlayed with flood inundation from modeling within each watershed). The additional "risk" here is not necessarily about the hydrologic inundation but more-so how it will impact the people in this area – in a detailed engineering study, yes, this area would be bound by the flood model. But we are trying to show here that when we model watersheds, which is what is done in practice, there are impacts elsewhere that involve society, and thus should be considered. We could have chosen to represent this ancillary "impact" in the Cypress watershed by the number of persons impacted by transferring flooding elsewhere – for purposes of ease, we chose to use the area of flood boundary. These inter-acting watersheds are particularly complex from a hydrological stance, due to the way water transverses over the watershed divide in certain storm events (this is not typical of most watershed divides). A fully coupled model was outside the scope of this study, and therefore we did not feel comfortable adding the Cypress Creek inundation bounds as part of our inundation area (B_i) since we did not perform extensive robust modeling here but rather made a very rough estimate according to inundation bound graphics from another study (Dunbar et al., 2019 – see Supplementary Information).

Section 3.2.3 – Weight Determination

This is THE key point of any MCA, making the difference between an exercise and a relevant field case. I cannot really understand how the authors determined the weights. I read about "discussions with Houston-area flood risk stakeholders, including governmental entities, interest groups, and specialized consulting firms"; the description continues with principles derived from the literature (lines 302-307); authors conclude by saying that "As participatory modelling is inherently qualitative, individual criterion weights will differ according to local conditions and stakeholder goals". All this is true, but what did they really do? From lines 308-312 I may understand that weights in table 2 are somehow just a reasonable proposal, not yet evaluated by stakeholders?

It is also very important to clarify that weights are not general but linked to the definition (and consequent variation ranges) for the indicators to be weighted. All this information set should be part of the discussion (with stakeholders) devoted to fixing the weights.

Again, weights are the key point. Selection criteria should be discussed. If such criteria are not robust, an extensive sensitivity analysis should be provided in order to give real value to the MCA.

Response: Our goal here was not to derive the final weights for optimizing the Addicks & Barker Reservoir system, as we posit that such weighting values cannot be finalized in such a manner since they include issues like social norms, vulnerability, and environmental harm, which all have many societal and diverse responses associated with each. Rather, we are attempting to showcase to stakeholders how a participatory planning approach can be used with MCDA – we are envisioning the spatial MCDA being a quick and intuitive visual manner to assess how if, for example, Stakeholder A really thought that social vulnerability should be given higher weight, while Stakeholder B really though that flood risk should be the only consideration, how when we consider each person/group's values, the outcomes shift. That was the point of the paper, to simply showcase this shift, and suggest that it should be included in the decision-making environment. As such, we learned from much of the social-sciences literature approaches that use weightings as proxies for values, eliciting them through models, and spurring very important discussions at the planning stage so that all stakeholder input can be considered and the decisions to weight X over Y, or vice-versa, has real implications. Hence, we maintain that the weighting here should definitely be subjective, as that is our goal.

To clarify this point, we added significant text to the Revised Manuscript (e.g., Lines 264-269) as well as a Limitations section (Section 5) explaining this proof-of-concept and how more robust weighting methods can be used, if the parties opt to do so, but we did not envision that being the case in a real-world application of our framework.

We selected the criteria based on local knowledge of the many issues that were impacted during Hurricane Harvey flooding. This will very likely be unique in each locale. A sensitivity analysis would showcase which criteria were sensitive to changes to the model but would not help with identifying which ones should be included in the first place. We posit that if a criterion ended up not being substantial to the end-result, the modelers would see this during the interactive spatial MCDA approach, and that itself would foster insightful discussions. We envisioned this being a very collaborative, participatory, iterative process, not driven by only modeling results using one value.

Section 3.3 – CBA

Benefits are evaluated in terms of a fixed damage/hectare, without considering any specification for the soil use / exposed elements (residential, agriculture, industrial, …). Please, add some consideration about the accuracy and robustness of the used fixed value (=0.478 M$/he).

Response: This fixed value is what was used within the USACE planning framework, which is what we are comparing against and recommending improving for decision-making. It is not common practice within the case-study area to assess flood reduction benefits in terms of their intended land use, although this could be an area of future study.

Section 3.4 – Integrated CBA + MCA

"Since the unique indicators contained different units of measurement ($/hectares, 0-100 risk) we used z-score normalization to transform the values to equivalent scales": this is not fully true. CB is non-dimensional (ranging 0-1 if benefits exceed costs, but later I understand expressed as 0-100); R and IF are also non-dimensional (ranging 0-100). Why was then the z-normalization used? This point should be clarified.

Response: Per Nardo et al. (2005), z-score standardization is commonly used to convert all indicators to a common scale that averages zero with standard deviation (SD) of one. The average of zero helps reduce aggregation distortions of extremes. It is the standardization approach used for the popular Environmental Performance Index (EPI, https://epi.yale.edu/). In our $IF_{E|S}$ results shown in Table 4, note how the social impact factors are quite low (30-40s), while the environmental impacts are much higher (60-80s). This happened to be how the spread of social risks and environmental risks played out within our watershed and the zones of flood inundation, but in another case study area, we could see the opposite, all highs, all lows or any combination. By not z-scoring these values, we might have skewed the results toward being highly contingent on the environmental risks. Or, we might have resulted in many of the Alternatives that had a very high CB_i, similar to the Baseline condition of 100 (e.g., A3, A5, A8), because their costs were quite high compared to the level of reduced flood inundation achieved, then our resulting T_i and ranking of Alternatives may have dis-favored some of these.

You are right about the rationale not being per the unit measurements. This reasoning has been clarified in Lines 343-344.

Moreover, the choice of the uniform weighting of the three indicators (CB, IF_E, IF_S) is an important part of the weight determination: what is the rationale under such choice? was it discussed with stakeholders? Was any sensitivity analysis performed?

Response: See response to comment in Section 3.2.3. These weights are intended to be changed by the stakeholders, according to local values, and not per a calculated impact on the model sensitivity (which we find to be too prescriptive for our intended goals of participatory learning through the modeling exercise presented here).

I have a wider doubt here, about the consistency of T, presumably as a consequence of not having understood how factors IFs (or Rs) are formed. Let us take two mitigation alternatives (A_1, A_2), with different costs C, different benefits B, different impacts IF which, for simplicity, we here limit to the number of people affected by the flood (we call it N). Let us imagine that $C_1>C_2$ but also $B_1>B_2$ (A_1 reduces the flooded area more than A_2) so that $CB_1=CB_2$. Thus, the CB component of T will be equal for the two cases, thus suggesting that T is an indicator of efficiency (intensiveness) rather than of efficacy (extensiveness). Let us imagine that $N_2>N_1$ (as A_1 reduces the flooded are more than A_2): what would happen to IF_1 and IF_2? Is their contribution to T consistent with an indicator of efficiency? What for all the other components of IF_E and IF_S?

Response: What you are describing is precisely our rationale for presenting this study. In the above hypothetical example, where Alternative 1 was more expensive but also produced the greatest flood benefit, while Alternative 2 was less expensive with much less flood benefit, these two Cost-benefit ratios could theoretically be equal. In such a case, we propose that additional considerations of looking at the environmental and social risks and impacts in the greater region could shed more light on which alternatives are preferred by the local stakeholders, by viewing things holistically. The hypothetically-equal CB_i's in this example would not change just because the social/environmental risk changed between the two Alternatives, *but the total risk (T_i) would change*, which is precisely our point. T_i should be used for rankings rather than CB_i.

Minor Points:

Line 25: "Hurricane Harvey": Add date of the event.

Response: This sentence was removed in the revised manuscript. The year 2017 was added to the first reference of Hurricane Harvey in the new manuscript, Line 116. The exact dates are also included when referencing the NOAA rainfall data used in the hydrological model, Line 214-215 (and the Supplementary Information).

Line 150: "Wealthy and middle-income populations face higher risks when located outside of federally-designated floodplains where flood insurance is voluntary". I cannot understand the reason of this higher risk.

Response: Their risks due to being flooded are not higher, but their ability to re-build after the storm are inextricably higher when lacking flood insurance but a legal requirement to continue paying on a ~ 30-year mortgage for a home that is now un-sellable in its current condition. This sentence was removed in the revised manuscript, and additional clarification was added to describe homes within the federally-demarcated flood zone and those where flood insurance is voluntary (see response to comment for Line 271).

Comment: Analyzed mitigation strategies (tab. 1) are those proposed in the USACE 2020 report. In particular, costs of the mitigation actions are derived from such reports. The reader would expect that also hydrological / hydraulic scenario are derived from the report but, apparently, it is not so, as modelling of such scenarios is discussed along the manuscript. Authors should clarify this point and discuss consistency of scenarios with associated costs. In particular, for scenario A7 I read (line 400) that the authors used a wider channel extension with respect to the USACE proposal: what about costs, were they modified accordingly?

Response: The modeling is conducted in this study to showcase to the decision-makers, i.e. those that wrote and use such dam mitigation planning reports, how the spatial MCDA approach can be easily integrated into the approach those engineers/modelers already use, which is HEC-HMS/HEC-RAS modeling. Only the outcomes of the HEC-HMS/HEC-RAS models are described qualitatively in such reports. The models were re-created here for validity of the approach and to obtain the resulting spatial flood bounds for each of the Alternatives presented by the USACE.

Regarding the particulars of noting how a wider channel was actually necessary than what the USACE assumed – this is of more local concern than utility for the overall theme of this paper; therefore, it was moved to the Supplementary Information material. We only noted this here to showcase that the preferred USACE mitigation strategy, once it enters into detailed engineering design, will likely require much more land buy-out than was being considered; therefore, our inclusion of the USACE cost estimate was conservative. Cost estimates at this early planning stage typically always have large contingencies built in, so this is still a valid approach to showcase our framework.

Line 235: "To standardize the point and polyline feature classes into spatially varied datasets, the Euclidean Distance method was applied. Euclidean distances convert feature layers into gridded datasets by assigning a value to each cell that indicates the distance of that cell to the nearest criterion, thus standardizing space and creating hotspots in multi-criteria decision making". Meaning and impact of this procedure is not clear to me.

Response: A popular reference for this approach within GIS hotspot mapping was added to the manuscript (Line 262) in case the reader would like to learn more about the Euclidean distance. This is a very common approach in spatial MCDA (e.g., below references, for a few examples), and is appropriate to list here.

Dell'Ovo, M., Capolongo, S., & Oppio, A. (2018). Combining spatial analysis with MCDA for the siting of healthcare facilities. *Land Use Policy*, *76*, 634-644.

Rufino, I. A GIS-based Multi-Criteria Analysis (MCDA) approach for water shortage risk mapping.

Demesouka, O. E., Vavatsikos, A. P., & Anagnostopoulos, K. P. (2013). Suitability analysis for siting MSW landfills and its multicriteria spatial decision support system: method, implementation and case study. *Waste management*, *33*(5), 1190-1206.

Tammi, I., & Kalliola, R. (2014). Spatial MCDA in marine planning: Experiences from the Mediterranean and Baltic Seas. *Marine Policy*, *48*, 73-83.

Aşilioğlu, F. (2021). GISimos MCDA land suitability model for ecotourism development. *Journal of Environmental Engineering and Landscape Management*, *29*(3), 200-214.

Cetinkaya, C., Özceylan, E., Erbaş, M., & Kabak, M. (2016). GIS-based fuzzy MCDA approach for siting refugee camp: A case study for southeastern Turkey. *International Journal of Disaster Risk Reduction*, *18*, 218-231.

Line 271: “The spatial risk associated with flood insurance was derived from national flood hazard zones and a repository of damaged structures in the community. It was assumed that residents within the FEMA 1% and 0.1% flood zones carried flood insurance, while 20% of all other residents had purchased voluntary insurance”. Please, provide comment about soundness of such assumption.

Response: Flood insurance is mandatory within the FEMA 1% and 0.1% flood zones. Persons cannot have a mortgage nor regular home insurance without also carrying FEMA flood insurance if they reside within one of these zones. Per Klotzbach et al. (2018), less than 20% of all damaged homes within Harris County impacted by Hurricane Harvey possessed active flood insurance, as many homes were located where insurance is voluntary. This reference has been clarified in Lines 171-173 and 310-311.

Table 3: I cannot reconstruct values for CB. Let us take alternative A3 for Addicks as an example. Reduction of flooded area is 466 he; when multiplied by 0.478 M$/he we obtain a damage reduction B = 223 M$; cost is here C = 5000 M$ (please, make indication of units coherent in tables 1 and 3) with a consequent CB = C/B = 2200% … not comparable with values in table 3 and with common sense. This clearly means that there is something I have not understood (I honestly tried) … please, clarify.

Response: Indication of units was added to the table (now Table 4) in revised manuscript.

In the above calculations, the benefit-cost ratio is being calculated instead of the cost-benefit ratio. Rather, the cost-benefit ratio is the inverse of the benefit-cost ratio. In the A3 example, Benefit over Cost = 223 M$ / 5000 M$ = 0.045. Therefore, Cost over Benefit = 1 – 0.045 = 0.955 = 95.5%.

Figure 6: I cannot understand spider graphs (c) and (d); I expect the same values as in plots (a) and (b) to be represented, but there is no coherence.

Response: (a) and (c) should correspond, as well as (b) and (d). This figure and caption have been updated to remove the spider graphs, since they are repetitive.

Suggestions on Organization of Manuscript:

Suggestion 1: Section 2.1: This relatively long paragraph appears as a continuation/specification of the literature review provided in the Introduction rather than a description in the methodology here used. Moreover, the scheme for “integrated flood management decision-making” in Fig. 1 is here presented but not really used (or, perhaps, not clearly explained). Consider better focusing all information within lines 18-104 with respect to the specific aim of the paper (case study).

Response: The introduction and background sections have been re-written to condense the information and highlight the paper goals. The introduction to the case study was streamlined within Section 1 and Section 2.1. Due to the significant inter-disciplinary impacts occurring within this watershed across three scientific domains, the background section was maintained but was re-written and re-organized to include only the information necessary for introducing the reader to the study and the alternative mitigation strategies for adequate understanding and reproducibility when reading the Methodology and Results sections.

Suggestion 2: Along the manuscript discussions are alternated between the hydrological/hydraulic scenarios (Sections 2.2.1, 3.1, 4.1) and the impact/damage/cost scenarios (remaining sections). I suggest to re-organize the material so that the sections for the two groups are presented all together, and the flux of information should become more coherent. This would also avoid some repetitions.

Response: The methodologies for the flood modeling, CBA, and spatial MCDA are unique and are maintained in separate sections; for clarity, additional sentences are described in Section 3 (Lines 199-205) to amalgamate these themes prior to reading.

The results of the approaches are integrated more thoroughly in Section 4. Also, much of the extra information regarding details of the flood modeling outputs are moved to the Supplementary Information documentation to reduce manuscript size and limit the discussion of results to what is pertinent for understanding how the combined CBA+MCDA could alter decision-making.

Suggestion 3: Lines 314-319: Here a general discussion about principles of a CBA is provided. However, here a simplified version of benefits evaluation is used. The general discussion could be omitted or moved to some introductory section.

Response: We are unsure what is referenced by a 'simplified version of benefits evaluation'. The cited articles (i.e., Ward, 2012 and Jonkman et al., 2004) describe how benefits, in the realm of water resources policy making, are informed by trade-offs in hydrological efficacy of the intended structural mitigation solution. Here, we used spatial trade-offs regarding flood inundation extent, which is what was also used in the USACE planning mitigation studies referenced in the Manuscript and here in the responses. This was to showcase how our integrated CBA+MCDA approach can fit within standard practicing planning paradigms. If the reviewer comment means that benefits evaluations can be applied in a more robust fashion, such as by assessing additional hydrological improvements amongst each of the alternatives (i.e., peak flow reduction, time to peak, etc.?), we chose the benefit of spatial flood risk due to its popularity within flood mitigation MCDA studies and within practicing dam infrastructure mitigation reports.

We have moved these sentences to the Introduction section, Lines 78-82, near the background discussion about MCDA to respond to the reviewer comment.