Editor Comments:

Dear Isabel Aitkenhead and co-authors,

Thank you for updating your manuscript "Validating a Tailored Drought Risk Assessment Methodology: Drought Risk Assessment in Local Papua New Guinea Regions".

Two referees have now provided reviews of the new version. Both of them are very satisfied with the work that you have done in the last round, and I mostly agree with them; still, one of them raised minor concerns that should be answered before the publication. Therefore, I would invite you to submit a revised version of your manuscript.

Would you please also provide an 'author's reply' to the reviewer and a track changes document between the old manuscript and the new one (you can include this as part of your 'author's reply').

I look forward to seeing the next version of your manuscript which I will not send out for further review, but rather, will make the decision myself, assuming no major items come up in the revised manuscript for which I need outside reviewers to aid me in my decision.

Regards, D. Molinari
NHESS Editor

Response to editor:

Dear D. Molinari,

Thank You for your response. We have responded to reviewer comments and have now provided a revised version of the manuscript and an author's reply. A track changes document is also provided. We have also made some minor grammatical edits to make indicator mentions consistent (in some cases all words in an indicator were capitalised or only the first word was capitalised).

We look forward to hearing your final decision.

Regards,

Isabella Aitkenhead and co-authors

Reviewer Comments:

Drought events across PNG occur mainly a result of two key climate drivers: El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD).

Resilient drought risk management consists of two key elements: proactivity and suitability. In this instance, proactivity is characterised by controlling a drought risk situation prior to the occurrence of a drought event, rather than responding to drought after it has reached a crisis level.

Commented [IA1]: From Referee #3: reference

Commented [IA2]: From Referee #3: Please indicate that you moved away from PNG to general drought risk management

Commented [IA3]: From Referee #3: reference

It is widely accepted that there are two types of risk assessments: static and dynamic. Dynamic drought risk assessments consider both the spatial and temporal aspects of droughts, using historic, periodically updated, and simulated data. Additionally, dynamic assessments incorporate not only hazard monitoring indicators, but also vulnerability and exposure indicators (Mosquera-Machado and Dilley, 2009). Most drought risk assessments that have been previously conducted have been static assessments (Hagenlocher et al., 2020). Static assessments provide an estimate of risk factors for a discrete moment in time and space, usually considering only one or two components of risk (e.g only hazard) (Aerts et al., 2018) (Hagenlocher et al., 2020). Dynamic assessments are recommended for use over static assessments as they provide a more holistic assessment of drought risk; drought risk is not static, but rather dynamic in both space and time (Hagenlocher et al., 2020).

Commented [IA4]: From Referee #3: reference

Commented [IA5]: From Referee #3: In PNG? Please indicate

Among the few studies seeking to validate a risk assessment methodology, various validation techniques have emerged (González Tánago et al. 2016).

Commented [IA6]: From Referee #3: Gonzales Tanago et al. did review vulnerability to drought studies. Please be clear on that.

These definitions remained clear throughout the assessment process, addressing the literature recommendation to consistently characterise drought risk as the risk of negative impacts as a function of three core components: hazard, exposure, and vulnerability (Hagnelocher et al. 2019).

Commented [IA7]: From Referee #3: Hagenlocher

It is important to note that:

- all types of droughts were considered when selecting indicators, as well as all major sectors across PNG provinces. This was done to provide a holistic risk index for PNG provinces, as each type of drought is known to impact PNG communities (Kuleshov et al., 2020), and each major sector experiencing the effects (Bhardwaj et al., 2021b).
- publicly accessible data was only available for certain indicators as data availability is poor in PNG, thus indicators which could have been more appropriate for use in hindsight had to be omitted.

Commented [IA8]: From Referee #3: What does this actually mean? Table 2 (please add reference here) only lists indices for 2 types of drought hazard

Commented [IA9]: From Referee #3: Which? List? Link?

Table 3 provides the generally accepted thresholds for each indicator in which 'no to mild drought risk, 'moderate drought risk', and 'severe to extreme drought risk' is likely signalled.

Commented [IA10]: From Referee #3: I doubt this, 4 references does not mean generally accepted. Please correct and state that you particularly reference to these publications. (you might add the explanatory text from the table here, and shorten there).

To calculate the hazard, vulnerability, and exposure indices, indicator data was first reclassified by a linear function (using the rescale by function tool in ArcGIS Pro) on a 1-10 scale and then standardised using *fuzzy* logic in ArcGIS Pro (Environmental Systems Research Institute (Esri) Inc., 2019).

Commented [IA11]: From Referee #3: I am not aware if it is statistically correct to standardise a standardised index (e.g SPI). Furthermore, using SPI-3 for annual standards is statistically not sound (just a feeling). Please explore.

Additionally, VHI primarily signals only agricultural drought, whereas SPI considers multiple drought types (meteorological, hydrological, and agricultural).

Commented [IA12]: From Referee #3: No it does not. It can be linked to the impacts of these drought types. But it is a meteorological drought index.

$$\mu_{gamma} = (\mu_{sum})^{\gamma} \times (\mu_{product})^{1-\gamma} \quad (7)$$

where μ_{gamma} is the calculated fuzzy membership function, γ is a parameter chosen between 0 and 1; μ_{sum} is the fuzzy algebraic SUM and $\mu_{product}$ is the fuzzy algebraic PRODUCT that is mathematically expressed in Equation 8 and 9 respectively (Dayal et al., 2018).

$$\mu_{sum} = 1 - \prod_{i=1}^{n}(1 - \mu_i) \quad (8),$$

$$\mu_{product} = 1 - \prod_{i=1}^{n}(\mu_i) \quad (9)$$

where μ_i is the fuzzy membership for the map, and i equals the number of maps to be combined. In the fuzzy gamma operation, γ=0 is equivalent to the fuzzy product and γ=1 is equivalent to fuzzy sum.

Commented [IA13]: From Referee #3: Can you summarise this into a risk formula like RI=f(....)

The researcher then observed the drought risk maps produced and determined the years in which a nationwide drought event was suspected in PNG. Since PNG is a highly variable nation, it is hard to stipulate that drought is occurring as a nationwide event if a handful of scattered provinces are at high risk, it is more suitable to consider drought risk across each of the four regions of PNG.

Commented [IA14]: From Referee #3: rephrase

Commented [IA15]: From Referee #3: rephrase- what is variable?

Data tables were created in Microsoft Excel for each indicator in each index. In the individual data tables, the indicator data value in question was instructed to change in 0.1 increments (spanning from 0.1 to 1). Using the What-If analysis function, these data tables were populated with output results, in this case the relevant index (hazard, vulnerability, or exposure) output in response to the change in the indicator value in question.

However, the effects of the 2019 drought event have not been widely discussed in peer-reviewed literature as it is such a recent event.

In non-drought years, where hazard is low but vulnerability and/or exposure remain high across PNG provinces, it is the time to be proactive and improve adaptive capacity.

The expert weighting scheme applied to the hazard indicators gave SPI a weighting of 0.75, and VHI 0.25.

Vulnerability and exposure indicators were static, using annually updated observed data, due to limited data availability. Although regularly updated data is not available for the vulnerability and exposure indicators, a holistic drought risk index still requires these two components in addition to the hazard component.

This research presents a preliminary validation of a tailored risk assessment methodology which is conceptually applicable to the local level.

The development of a tailored, meaning highly specific to the area under investigation, drought risk assessment methodology has been recognised as vital to improving risk knowledge for the development of resilient drought risk management strategies in vulnerable communities (Wilhelmi and Wilhite 2002).

Due to data restrictions, the vulnerability and exposure components of the risk assessment consisted of annually updated, static indicators.

This is a critical step commonly omitted from the risk assessment process ((Blauhut 2020, Hagenlocher et al., 2019 and González Tánago et al. 2016).

Overall, this research establishes an essential foundation for tailored and accurate drought risk assessments in Pacific SIDS, using drought in PNG as a case study.

Commented [IA16]: From Referee #3: Please phrase this non-excel style

Commented [IA17]: From Referee #3: Any idea why?

Commented [IA18]: From Referee #3: Can you derive any of this from your study?

Commented [IA19]: From Referee #3: You might comment on my previous question about standardising standardised indices here.

Commented [IA20]: From Referee #3: You shall claim more dynamic input data? Better national statistics?

Commented [IA21]: From Referee #3: Don't be too hard, you did well. Maybe "presented an effective solution to test"

Commented [IA22]: From Referee #3: You might bring this up in the abstract.

Commented [IA23]: From Referee #3: At some point you raised 'semi-dyamic'. Annual updated is not static per se, but of course not really dynamic. You might consider to stick with 'semi' and apply this accordingly in throughout the manuscript (and in the title). Anyway, make clear what your data is. Either or, it feels mixed.

Commented [IA24]: From Referee #3: (

Commented [IA25]: From Referee #3: meaning

Response to reviewer comments:

In response to the first reviewer comment, a reference has been added at the end of the following sentence:

Drought events across PNG occur mainly a result of two key climate drivers: El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (Chua et al., 2020).

In response to the next couple of reviewer comments, a clarification to the following sentence has been provided to ensure readers understand we are speaking of general resilient drought risk management, not just management specific to PNG. Additionally, a reference has been added to the next sentence:

~~Resilient~~ Globally, resilient drought risk management consists of two key elements: proactivity and suitability. In this instance, proactivity is characterised by controlling a drought risk situation prior to the occurrence of a drought event, rather than responding to drought after it has reached a crisis level (Pulwarty and Sivakumar 2014).

A reference was added for the following sentence:

It is widely accepted that there are two types of risk assessments: static and dynamic (Hagenlocher et al., 2020; Wilhite et al., 2014).

A clarification was made to the following sentence in response to the reviewer comment of whether this sentence was referring to studies conducted just in PNG:

Most drought risk assessments that have been previously conducted on both the global scale, and specifically for PNG, have been static assessments (Hagenlocher et al., 2020).

To clarify that we are not just referring to risk assessment validation but consider vulnerability assessment validation techniques as well (as these are still relevant to our methodology), we have added the following information into the sentence:

Among the few studies seeking to validate a risk assessment methodology, including those seeking to validate an assessment solely focused on one component of risk like vulnerability, various validation techniques have emerged (González Tánago et al. 2016).

This allows for the González Tánago et al. 2016 reference to be more appropriately used.

A spelling mistake has been made for the following sentence:

These definitions remained clear throughout the assessment process, addressing the literature recommendation to consistently characterise drought risk as the risk of negative impacts as a function of three core components: hazard, exposure, and vulnerability (Hag~~n~~enlocher et al. 2019).

The reviewer recommended to refer to Table 2 here, but we believe it is more appropriate to add a reference to the Supplementary materials document, as the tables included in the supplementary materials describe each indicator, including whether they are relevant to the different types of drought and sectors in PNG. We believe that we consider meteorological, agricultural, and socioeconomic drought through our compilation of vulnerability and exposure indicators, but we do recognise that we were unable to examine hydrological drought. This is clarified in the following section:

It is important to note that:

- all types of droughts were considered when selecting indicators (Supplementary Materials), as well as all major sectors across PNG provinces. This was done to provide a holistic risk index for PNG provinces, as each type of drought is known to impact PNG communities (Kuleshov et al., 2020), and each major sector experiencing the effects (Bhardwaj et al., 2021b). However, it was particularly difficult to find indicators suitable for the study context that inform on hydrological drought. Thus, this drought type could not be examined in the PNG drought risk assessment.

To be clear as to which indicators we are referring too when we talk about restricted data availability and subsequent exclusion from the risk assessment, the following clarifications have been made to the section:

- publicly accessible data was only available for certain indicators as data availability is poor in PNG (all indicators ultimately selected for use in the risk assessment had publicly accessible data available), thus indicators which could have been more appropriate for use in hindsight had to be omitted. For example, Avg. household consumption of staple food could have been a useful vulnerability indicator, particularly informing on food insecurity. However, data availability was too scarce across PNG for it to be included in the risk assessment (Supplementary Materials).

As per the reviewer comment, we have deleted the term 'generally accepted' in the following section and just explain the thresholds as 'accepted'. We also clarify that they are accepted by several studies but not all studies. The specific sources used to inform the thresholds are listed. This information is also listed in the Table 3 description. Although the referee said we could shorten the Table 3 explanation if we were to

provide more information here, we have decided to keep the explanation the same, so that when referring to the table separately, readers can properly gauge what is being presented.

Table 3 provides ~~the generally~~ accepted thresholds, outlined by several other studies (Rahmati et al., 2020; Nasrollahi et al., 2018; Aitkenhead et al., 2021), the advice of the PNG National Weather Service, as well as past data trends in PNG (Chua et al., 2020), for each indicator in which 'no to mild drought risk, 'moderate drought risk', and 'severe to extreme drought risk' is likely signalled.

To respond to the comment '*I am not aware if it is statistically correct to standardise a standardised index (e.g SPI). Furthermore, using SPI-3 for annual standards is statistically not sound (just a feeling). Please explore.*' I would like to explain that it is okay to standardise an indicator like SPI. It has been done in several past reputable studies (e.g Aitkenhead et al. 2021; Dayal et al., 2018). As we are comparing several different indicators with various data ranges, we need to standardise them to have the same data range before index calculations can commence. This needs to occur for already standardised indicators like SPI, as they are still on different scales. We wanted a standardised range for indicators as 0-1. SPI values range beyond this, thus they needed to be standardised with our fuzzy logic method, to be on the 0-1 scale. Additionally, it seems that there might be some confusion as to if we are just using one individual SPI-3-month value to represent the entire year when conducting our annual risk assessment. This is not the case. We took the average of the 12 individual 3-month SPI values for each month in the year, to get the annual average value used in the risk assessment. To clarify, we have added some more information in Table 2 for SPI and VHI (there may be similar confusion for VHI too):

Spatial- Average value for each province. Temporal- monthly and averaged yearly data available from 2001 onwards (3-month SPI values from the month of January to the month of December were averaged to get annual values). Updated every month.

Spatial- Average value for each province. Temporal- monthly and averaged yearly data available from 2014 onwards (3-month VHI values from the month of January to the month of December were averaged to get annual values). Updated every month.

To clarify that SPI is not a meteorological, hydrological, and agricultural drought indicator, rather a meteorological indicator that can be linked to the impacts of additional drought types, edits have been made to the following sentence:

Additionally, VHI primarily signals only agricultural drought, whereas SPI is a meteorological drought hazard indicator which can be linked to the impacts of ~~considers~~ multiple drought types (not only meteorological but also ~~meteorological,~~ hydrological~~,~~ and agricultural).

In response to the comment of whether we can summarise the fuzzy gamma overlay formulas into an overall risk formula, we recognise that it may be easier to understand if we summarised into a simpler risk equation. However, it is most accurate and more detailed to explain the calculation of the risk index with the equations we have already included. As we have already stated that we take risk as an equal combination of hazard, vulnerability, and exposure indices, we think it might be redundant to further provide a simplified risk formula (as it would just be risk=hazard+vulnerability+exposure).

Edits have been made to the following section given the reviewer comments about rephrasing and clarification:

Through observation of the produced drought risk maps, ~~The researcher then observed the drought risk maps produced and determined~~ the years in which a nationwide drought event was suspected in PNG were determined. Since PNG is a highly variable nation (in both climatic and geographic characteristics), it is hard to stipulate that drought is occurring as a nationwide event if a handful of scattered provinces are at high risk, it is more suitable to consider drought risk across each of the four regions of PNG.

A section of text in Methodology: Part 4 was rephrased in response to the reviewer comment 'Please phrase this non-excel style'. The section was changed from "Data tables were created in

Microsoft Excel for each indicator in each index. In the individual data tables, the indicator data value in question was instructed to change in 0.1 increments (spanning from 0.1 to 1). Using the What-If analysis function, these data tables were populated with output results, in this case the relevant index (hazard, vulnerability, or exposure) output in response to the change in the indicator value in question.**" to "**Conducting the sensitivity analysis, the value of each indicator in question was changed in a stepwise manner from 0.1 to 1 with 0.1 increment and outputs for the relevant index (hazard, vulnerability, or exposure) were tabulated; data tables were produced using Microsoft Excel with the What-If analysis function.**"**

To address the reviewer question of why for the following statement "However, the effects of the 2019 drought event have not been widely discussed in peer-reviewed literature as it is such a recent event.", we answer that it is most likely because the drought research and response space is still quite reactive, despite efforts to transition to a proactive mindset. Thus, drought studies tend to lag and are not produced until after events occur. We have added the following sentence in the discussion to explain this "Drought investigations usually occur after the fact, sometimes years after an event occurs. This is most likely because the drought research and response space is still largely reactive, despite efforts towards proactivity (Wilhite et al., 2014)."

In response to the reviewer comment 'Can you derive any of this from your study?' for the sentence "In non-drought years, where hazard is low but vulnerability and/or exposure remain high across PNG provinces, it is the time to be proactive and improve adaptive capacity.", we believe that we sufficiently discuss how proactive approaches and adaptive capacity can be informed by our study in section *4.3 2015 monthly case study: transition of drought*. In the section we discuss how proactive approaches may have been implemented in the lead up to the peak of the 2015-2016 drought, had our risk assessment information been available at the time.

For the sentence "The expert weighting scheme applied to the hazard indicators gave SPI a weighting of 0.75, and VHI 0.25." the following reviewer comment was provided 'You might comment on my previous question about standardising standardised indices here.'. As we do not believe this is a significant point of discussion (as the standardisation of drought indicators, including SPI, is common practice throughout drought risk assessment studies e.g Aitkenhead et al. 2021 and Dayal et al., 2018), we have chosen not to elaborate on this here.

The reviewer commented 'You shall claim more dynamic input data? Better national statistics?' for the following sentences "Vulnerability and exposure indicators were static, using annually updated observed data, due to limited data availability. Although regularly updated data is not available for the vulnerability and exposure indicators, a holistic drought risk index still requires these two components in addition to the hazard component.". In response to this comment, we have added a sentence in this section to clarify that we ideally would like more dynamic data, and that there is a need for more consistent socio-economic statistics in PNG.

Ideally, more dynamic data (e.g updated monthly rather than annually) would be used for these indicators, but this can only happen if consistent socio-economic statistics become available for PNG.

The reviewer suggestion was implemented for the following sentence:

This research presented an effective solution to test the ~~presents a preliminary~~ validation of a tailored risk assessment methodology which is conceptually applicable to the local level.

As per the reviewer comment to potentially talk about how the development of a tailored drought risk assessment is vital for improving risk knowledge, we have added the following sentence into the abstract:

A tailored, meaning highly specific to the area under investigation, drought risk assessment methodology is key for expanding risk knowledge in vulnerable communities.

In response to the comment 'At some point you raised 'semi-dyamic'. Annual updated is not static per se, but of course not really dynamic. You might consider to stick with 'semi' and apply this accordingly in throughout the manuscript (and in the title). Anyway, make clear what

your data is. Either or, it feels mixed', we recognise that the reviewer is correct in saying that vulnerability indicators are not technically static, as they are eventually updated yearly or every second year, with some exposure indicators also not technically static. Thus, these indicators will be described as semi-dynamic rather than static throughout the text. Thus, we have made edits to describe the hazard index as dynamic, the vulnerability index as semi-dynamic, and exposure index as having both static and semi-dynamic indicators. Which results in a semi-dynamic risk assessment.

The following edits have been made:

In 2.2 Study Design the following edits have been made:

The assessment is deemed as semi-dynamic as it has a dynamic hazard component, that can be updated monthly and includes monitoring indicators with data on 3-month cumulative timescales, but also includes more semi-dynamic and static components of vulnerability and exposure, which are updated annually or in some cases (e.g. elevation) remain fixed.

In 4.5.2 Static Indicators:

Vulnerability and exposure indicators were semi-dynamic or static, using annually updated observed data or fixed data~~, due to limited data availability~~. Fixed data for indicators like Land Use and Elevation is expected; these indicators are naturally static (Safavi et al., 2014). Whereas the data for indicators like Staple Crop Tolerance Score, Agricultural Occupation, Percentage of Children Weighed at Clinics Less than 80% Weight for Age 0 to 4 years old, and Key Crop Replacement Cost (for vulnerability), along with Population Density and Access to Safe Drinking Water (for exposure), was semi-dynamic due to limited data availability. Ideally, more dynamic data (e.g updated monthly rather than annually) would be used for these indicators, but this can only happen if consistent socio-economic statistics become available for PNG. Although regularly updated data is not available for ~~the~~ all vulnerability and exposure indicators, a holistic drought risk index still requires these two components in addition to the hazard component. The hazard indicators used were dynamic, incorporating regularly updated monitoring data. The hazard variables used were 3-month cumulated values (3-month SPI and VHI), which potentially reduces the informative value of the hazard and risk index to give a warning of high risk early enough in advance to act proactively. However, this risk assessment is not intended to predict drought events before they happen, it is intended to be used to determine the risk of a drought event occurring and the relative impact that might be faced by specific PNG provinces during a drought. Overall, the semi-dynamic nature of this assessment is not likely a limitation that will reduce the value of this preliminary risk assessment methodology.

In 4.6 Research Significance and Conclusions:

This study adopted the drought risk definitions consistent with those recommended by Hagenlocher et al. (2019). No such study has been conducted previously in PNG, where clearly defined hazard, vulnerability and exposure components are included to assess risk for all provinces. The assessment was intended to be dynamic, but limitations saw that it was only semi-dynamic. Due to data restrictions, the vulnerability ~~and exposure~~ component~~s~~ of the risk assessment consisted of annually updated, ~~static~~ semi-dynamic indicators. The exposure component was also semi-dynamic, with fixed data for naturally static indicators, and annually updated data for the indicators that would ideally be more dynamic. Whereas the hazard component included solely dynamic factors. Thus, the overall approach is deemed a semi-dynamic drought risk assessment. For the assessment to become wholly dynamic, socio-economic data needs to become more readily available. The constrained availability of relevant, reliable, and updated data is recognised as majorly detrimental to drought risk assessments across the world (González Tánago et al. 2016). The semi-dynamic assessment can still provide important results, more static assessment is useful for identifying where the origins and drivers of drought risk exist, and the areas that are of priority for long-term adaptation plans (Blauhut 2020, Hagenlocher et al., 2019 and González Tánago et al. 2016).

The following small edit was made to the sentence as per review comment:

This is a critical step commonly omitted from the risk assessment process ~~(~~(Blauhut 2020, Hagenlocher et al., 2019 and González Tánago et al. 2016).

Upon reflection of the reviewer comment asking for what we mean by accurate in the sentence "Overall, this research establishes an essential foundation for tailored and accurate drought risk assessments in Pacific SIDS, using drought in PNG as a case study.", we have decided that accurate is not the best word to use here. We have now changed it to "Overall, this research establishes an essential foundation for tailored and ~~accurate~~ valid drought risk assessments in Pacific SIDS, using drought in PNG as a case study.". Valid seems more appropriate to use rather than accurate, as we tested the validity of the assessment rather than the accuracy.