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Validating a tailored drought risk assessment methodology: drought risk assessment in local Papua New Guinea regions

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Supplementary Materials

S1. Table showing drought hazard indicators that were investigated and found to be fit for use when measuring drought hazard in PNG provinces.

Indicator	Past use description	Listed by WMO?	Reason for Selection
SPI	Used in similar drought assessments (Nasrollahi et al., 2018; Fallon et al., 2018). It has been evaluated and proven to be effective by (Chua et al., 2020) through a case study investigating how well SWCEM precipitation products characterised drought in PNG during the 2015/2016 El Niño event.	Yes-Green.	SPI is a space-based monitoring drought hazard indicator. It can inform on whether an El Niño or La Niña event is occurring; low precipitation is most often associated with an El Niño phase in many PNG provinces, vice versa. It has been given 'green light' by World Meteorological Organisation (WMO) and recommended as starting point for drought hazard assessment (Svoboda and Fuchs, 2016). It has also been proven reliable as a drought hazard indicator in a previous drought detection study in PNG (Chua et al., 2020) and used consistently in past drought risk assessments conducted in other countries with a drought-prone climate like PNG (Khan et al., 2008; Rahmat et al., 2014). Quality data for SPI is available from Space-Based Monitoring Observations available through National Oceanic Atmospheric Administration (NOAA) and Japan Aerospace Exploration Agency (JAXA).
VHI	Used in a study of agricultural drought in Zimbabwe (Frischen et al., 2020). It has been proven to be highly effective by (Chua et al., 2020) through a case study investigating how well SWCEM precipitation products characterised drought in PNG during the 2015/2016 El Niño.	Yes-Green	VHI is a spaced-based monitoring drought hazard indicator that can inform on whether an El Niño or La Niña event is occurring. Chua et al. (2020) determined VHI to be highly effective in indicating the spatial and temporal aspects of the severe 2015/16 El Niño event in PNG. It has been given the 'green light' by World Meteorological Organisation (WMO) due to its ease of use and reliability (Svoboda and Fuchs, 2016). Furthermore, it has been proven useful through consistent inclusion in past drought risk assessments conducted in other countries with a drought-prone climate like PNG (Dalezios et al., 2014; Frischen et al., 2020). The weighting of VHI could be reduced in this study, as it is primarily an indicator for agricultural drought risk, and although the agricultural impact of drought is of key focus in this research, a more holistic investigation is intended with additional focus on other sectors. Quality data for VHI is available through NOAA and JAXA.

S2. Table showing additional drought hazard indicators investigated and found to be unfit for use when measuring drought hazard in PNG provinces.

Indicator	Past use description	Listed by WMO?	Reason for Omission
Rainfall Deficiency	Rainfall deficiency is a major factor responsible for occurrence of drought as it is the cause of subsequent soil moisture shortage for crops (Dayal et al., 2018).	No	This indicator is too broad and has questionable accuracy at the provincial level (Svoboda and Fuchs, 2016). There are more efficient indicators that similarly measure water availability that would be preferable.

Soil Moisture Deficit Index	Has been used to indicate salinity levels (Martínez-Fernández et al., 2016). This is important as salinity levels affect agricultural production (Martínez-Fernández et al., 2016).	Yes- Red	This indicator is marked with a red light by WMO because of significant obstacles that threaten the ability for use of this indicator in research. This indicator requires weekly calculations at different soil depths, which is complicated to collect and calculate (Svoboda and Fuchs, 2016).
Standardised Water Level Index	It has been used in past studies to evaluate the hazard level of drought through the identification of the amount of salt in the water, hence by its salinity concentration (Sahani et al., 2019).	Yes- Yellow	This indicator is marked as yellow due to some challenges when using this indicator for research. This indicator produces similar results to SPI, but it uses groundwater or well-level data instead of precipitation, which is more complex to collect and calculate (Svoboda and Fuchs, 2016).
Normalized Difference Vegetation Index (NDVI)	NDVI is used to identify and monitor droughts that are affecting agriculture specifically (Svoboda and Fuchs, 2016). It is a remote sensing indicator that has openly available data from spaced-based monitoring organisations like NOAA (Svoboda and Fuchs, 2016).	Yes- Green	This indicator is a popular drought hazard indicator, but it has several limitations reducing the accuracy and efficiency for use in indicating drought. Past studies have shown that anomalies are common in temporal NDVI data (Gaikwad et al. 2015). Additionally, NDVI is known to be influenced by other atmospheric and environmental factors that are not related to drought. This threatens the accuracy of NDVI for indicating drought hazard conditions as NDVI values may reflect non-drought-related stress conditions in vegetation (Jiménez-Donaire et al. 2020).

S3. Table showing drought vulnerability indicators that were investigated and found to be fit for use when measuring drought vulnerability in the PNG Provinces.

Indicator	Past use description	Reason for Selection
Percentage of Children Weighed at Clinics Less than 80% Weight for Age 0 to 4 years old	Used in reliable past studies investigating the effects of drought within study areas with similar socioeconomic characteristics as PNG (Hirvonen et al., 2020; Cooper et al., 2019).	This is an indicator specific for the health sector. It has been used in reliable past studies investigating the effects of drought within areas of similar socioeconomic characteristics as PNG (Hirvonen et al., 2020; Cooper et al., 2019). The study by Hirvonen et al. (2020) used this indicator in a case study of the 2015 drought event in Ethiopia to determine the association between drought risk and health impacts. The socio-economic characteristics, including those of the health sector, of Ethiopia are like PNG as they are both developing nations. Both Ethiopia and PNG have malnutrition as a main health concern, as well as lack of access to clean water and sanitation. Given the similarities between Ethiopia and PNG, and the past usefulness of this indicator in the study by Hirvonen et al. (2020), it is likely that this indicator will be an efficient drought vulnerability indicator for PNG provinces. Data is available at the provincial level in PNG for recent years from PNG National Weather Service (NWS) and United Nations Development Programme (UNDP).
Key crop replacement cost	Used in reliable past studies investigating the effects of drought within study areas with similar socioeconomic characteristics as PNG	This vulnerability indicator is an indicator specific for the economic sector, considering socioeconomic drought affects. It has been used in reliable past studies assessing the effects of drought within areas with similar socioeconomic characteristics as PNG (Mohmmed et al., 2018; Abid et al., 2016). A drought vulnerability assessment conducted by Mohmmed et al. (2018) in five agricultural-based regions of Gadaref, Eastern Sudan used key crop replacement as an indicator to examine the susceptibility of farmers. The assessment resulted in the identification of the most vulnerable regions in the study area. Sudan has similar socioeconomic characteristics to

	(Mohmmed et al., 2018; Abid et al., 2016).	PNG, as they are both developing countries according to the United Nations General Assembly. Like PNG, Sudan has a population reliant on agriculture for their livelihood. Due to the similarity between Sudan and PNG regarding socio-economic factors, key crop replacement cost is likely an effective indicator of drought vulnerability in PNG provinces. Data is available on the provincial level for recent years from PNG National Weather Service (NWS) and United Nations Development Programme (UNDP).
Staple Crop Tolerance Scores	Used in reliable past studies assessing drought vulnerability within areas with similar socioeconomic characteristics as PNG (Antwi et al., 2015; Ayantunde et al., 2015).	This vulnerability indicator is specific for the environment and agricultural sector, considering agricultural drought effects. It has been used in reliable past studies investigating drought vulnerability in areas with similar socioeconomic characteristics as PNG (Antwi et al., 2015; Ayantunde et al., 2015). In the study by Ayantunde et al. (2015) staple crop tolerance score was used as an indicator in a drought vulnerability assessment of three agro-pastoral communities in Niger. Niger is a least developed country with similar socio-economic characteristics to PNG, with a like reliance on the agricultural industry. As in PNG, farmers in Niger are frequently report detrimental drought impacts to crops. Due to the related socio-economic characteristics of PNG and Niger, this indicator is likely effective for assessing drought vulnerability in PNG provinces. Data is available on the provincial level for recent years from PNG National Weather Service (NWS) and United Nations Development Programme (UNDP).
Agricultural Occupation (% of population employed in agriculture)	Used in reliable past studies investigating drought vulnerability within areas with similar socioeconomic characteristics as PNG (Nasrollahi et al., 2018; Mainali and Pricope, 2019).	This vulnerability indicator is specific for the economic and agricultural sector. It has been used in reliable past studies investigating within similar countries to PNG (Nasrollahi et al., 2018; Mainali and Pricope, 2019). A study by Mainali and Pricope (2019) in Nepal used agricultural occupation as an indicator for mapping climate vulnerability of ten drought-prone villages. Nepal and PNG have a similar reliance on the agricultural industry, with a significant amount of the populations employed in agriculture. The similarity between PNG and Nepal regarding the reliance on agriculture, as well as the usefulness of this indicator in the past study by Mainali and Pricope (2019) means that this indicator is most likely effective for this research. Data is available on the provincial level for recent years from PNG National Statistical Office.

S4. Table showing additional drought vulnerability indicators unfit for use when measuring drought vulnerability in PNG provinces.

Indicator	Past use description	Reason for Omission
Social dependency (% population >15 and <64 years old)	Used by Frischen et al. (2020) as a drought vulnerability indicator in a drought risk assessment in Zimbabwe. Like PNG, Zimbabwe is severely affected by drought leading to adverse impacts and has a heavy reliance on the agricultural sector. The risk index gave differing risk severity levels for the different regions of Zimbabwe (Frischen et al. 2020).	Although this indicator has been used in past studies in areas with similar characteristics to PNG, it is unlikely this would be a representative indicator of drought vulnerability in PNG provinces. There is unlikely to be spatial variation in indicator data. PNG has a similarly young population across all provinces.
Avg. household consumption of staple food	This indicator informs on food security in households (Ibok et al. 2019). In a study by Islam et al. (2022) in Bangladesh, this indicator was used to indicate climate risk of vulnerable households.	Data is severely scarce for this indicator in PNG. Therefore, it cannot readily be used as an indicator for drought vulnerability in PNG provinces.

Average Household Income	This has been investigated as an indicator of drought vulnerability in previous studies, like Stenekes et al. (2012). Stenekes et al. (2012) revised indicators of drought vulnerability across the Murray-Darling Basin in Australia and proposed indicators for future risk assessments. Average household income was proposed as a vulnerability indicator.	As a least developed country, PNG is expected to have low average household income across most provinces. The likely similarity of data for this indicator across PNG provinces reduces the value for informing on PNG's varying vulnerability levels.
Education (Literacy rate in at least one language % of population over 10 years old)	Education has been used in past risk assessment studies as an indicator for drought vulnerability, and particularly for adaptive capacity. In an investigation of drought risk in Nigeria, Ibok et al. (2019) used education level as a drought vulnerability indicator. Although Nigeria is a more developed country compared to PNG, both countries have low literacy rates compared to western countries like Australia. This has the potential to affects the ability of locals to independently implement effective drought management strategies.	Education levels are similarly low across all PNG provinces, including the National Capital District, according to a survey conducted in five provinces of PNG from 2006-2011, by the Asia South Pacific Association for Basic and Adult Education (ASPBAE). As there would be little variation between provinces, it would not be valuable for informing on the varying drought vulnerability levels in PNG.
Key crop production	In an investigation of drought vulnerability in India, crop production was proposed as a useful indicator (Saha et al. 2012). Similarly, crop production was used as an indicator in a drought vulnerability assessment conducted in Indonesia, which specifically focused on food security impacts (Pangan and Pertanian, 2015).	The past use of this indicator suggests that it has the potential for use in PNG. However, in this research key crop production is seen more of an impact factor rather than a vulnerability factor. Staple crop tolerance or crop replacement cost could be more specific indicators for indicating vulnerability to the effects of drought. For example, if a province was to have low crop tolerance scores, it is likely that in a drought period the production of crops would be reduced.

S5. Table showing drought exposure indicators that were investigated and found to be fit for use when measuring drought exposure in PNG provinces.

Indicator	Past use description	Reason for Selection
Land Use (type)	Used in reliable past studies investigating the effects of drought within study areas with similar socio-geographic characteristics as PNG (Rahmati et al., 2020; Shahid and Behrawan, 2008).	This is an exposure indicator specifically considering the environment and agricultural sector. It has been used in reliable past studies like in Shahid and Behrawan (2008), where it was used as an exposure indicator within a vulnerability index for drought in Bangladesh. In the Bangladesh study, exposure was not considered as its own component of drought risk, it was included as part of the vulnerability component. Although the methodology of Shahid and Behrawan (2008) differs to the one used in this study, the consideration of land use as an exposure indicator is deemed appropriate for assessing risk in PNG. Like PNG, Bangladesh has a large portion of land use dedicated to agricultural activities which has been affected by drought in the past. Data is available for recent years from PNG National Weather Service (NWS) and United Nations Development Programme (UNDP).
Elevation (type) (Highland/Lowland/Average)	Used in reliable past studies assessing the effects of drought within areas with similar socio-geographic	Elevation is an exposure indicator specifically considering the environment and agricultural sector. Elevation affects the severity of drought in PNG, with highland areas known to be most exposed to the effects of drought in the form of frost. In the 2015/2016 drought event in PNG, high altitude areas experienced severely detrimental impacts on crops (Iese et al. 2021). Furthermore, elevation has been used as an indicator in past studies investigating and

	characteristics as PNG (Han et al., 2015; Sun et al., 2020).	assessing the effects of drought within study areas with similar socio-geographic characteristics as PNG (Han et al., 2015; Sun et al., 2020). Data is available from open-sourced GIS platforms.
Population Density	Used in reliable studies investigating drought effects within areas with similar socio-geographic characteristics as PNG (Nasrollahi et al., 2018; Pei et al., 2018).	Population density is an exposure indicator for the social sector; it is an indirect indicator for infrastructure, health service, and water accessibility. It has been used in past studies investigating the effects of drought (Nasrollahi et al., 2018; Pei et al., 2018). More direct indicators of accessibility like access to roads or access to markets would be better for use here, however, data availability for such indicators is extremely limited in PNG. Thus, population density is seen as the best possible indicator for accessibility in the exposure index. Data is available for recent years from PNG National Statistical Office.
Access to safe drinking water (% of population with access to safe drinking water)	Used in past studies assessing the drought exposure within areas with similar socio-geographic characteristics as PNG (Limones et al., 2020; Frischen et al., 2020).	Access to safe drinking water is an indicator of drought exposure, particularly considering hydrological drought and its impacts on the social sector. If communities have limited access to safe drinking water, they will be more exposed to detrimental drought effects as they may have to travel further to additional water sources in times of drought (Limones et al., 2020). It has been used in reliable studies investigating drought exposure within areas with similar socio-geographic characteristics as PNG (Limones et al., 2020; Frischen et al., 2020). When investigating an approach for identifying high drought risk areas in data-scarce regions of southern Angola, Limones et al. (2020) use access to safe drinking water as an indicator of drought exposure. Angola is expected to have similarly restricted access to safe drinking water in some areas, just as with regions in PNG, as it is a least developed country with locals having limited access to core resources. In the study by Limones et al. (2020) this indicator was able to help in the identification of high-risk areas to drought in Angola. The similarity between Angola and PNG mean it is likely that this indicator is suitable for use in informing a drought exposure index in PNG as well. Data is available for this indicator for recent years from PNG National Statistical Office.

S6. Table showing additional drought exposure indicator unsuitable for use when measuring drought exposure in PNG provinces.

Indicator	Past use description	Reason for Omission
Access to roads	This indicator has been used in several past studies conducting risk assessments (Luh et al. 2015; Nakamura et al. 2019). Nakamura et al. (2019) used this as an indicator for exposure in an assessment in Ethiopia. Results suggested that remote communities with roads connecting them to markets and other services had less exposure to drought impacts.	This indicator would be useful for indicating drought exposure; however, data is not available/accessible on the provincial level for PNG. In the future if data becomes available, then this indicator should be considered for the drought exposure index.
Access to land resources	This indicator was used in a study by Ghimire et al. (2010) which describes access to land resources as total landholding in an area. It is explained that the higher the landholding, the lower the exposure to drought impacts. This is because landholding can serve as a cushion to absorb financial shocks by utilising it as collateral for loans or sale when needed.	This indicator is not appropriate for use in PNG, due to the nature of customary clan ownership, which over 95% of land in PNG remains under (Chand 2017). Clans rather than individual people hold most of the land in PNG provinces. Data for clan land holdings is scarce as the principles of land tenure that arise from custom are not commonly written down (Chand 2017).

Access to technology	Ghimire et al. (2010) use this indicator in an assessment of drought risk, explaining that this indicator is evidence for the adoption of improved varieties of crops or horticultural plants. Thus, access to technology likely reduces exposure.	This indicator is likely not representative of varied drought exposure among PNG provinces as it would be expected that access to technology would be relatively low across PNG. Additionally, data for this indicator is limited on the provincial level in PNG.
Access to social networks	Ghimire et al. (2010) use this indicator, defining it as membership in social, political, or economic organisation. It is seen that access to social networks decreases drought exposure (Ghimire et al. 2010).	Data is restricted for this indicator on the provincial level in PNG. Furthermore, there are more comprehensive indicators available.
Access to market	Previous drought risk investigations have used access to market as an exposure indicator (Ghimire et al. 2010; Mdungela et al. 2017). It is defined as the walking distance to reach the nearest public transportation service or walking distance to the market itself. The lesser the distance, the more access to a market, which in turn means lower exposure.	Data is restricted for this indicator on the provincial level in PNG. It would be useful to incorporate this indicator in the risk assessment in the future if data becomes available.
On-farm diversification	Mdungela et al. (2017) used this as an indicator of drought exposure in an investigation of drought risk. On-farm diversification includes the mixing of crops and the inclusion of drought-resistance crops on farms. Mdungela et al. (2017) explain that the more diverse a farm is, the less exposed it is to drought conditions.	Data is restricted for this indicator on the provincial level in PNG. Currently, it is expected that information regarding farming types is included in the land use indicator. However, this indicator would be more specific for use if data was available.
Aridity Index	The Aridity Index has been used in past drought risk assessment studies like Lindoso et al. (2014). It is a real-time indicator in which water balance is considered with the comparison of the actual aridity to the normal aridity for a given period (Svoboda and Fuchs, 2016).	Not applicable to long-term or multi-seasonal events (Svoboda and Fuchs, 2016). Thus, it would not be appropriate to measure long-term drought; long term drought affects PNG frequently.

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