Co-development of vulnerability and risk assessment framework and methodology for Nepal

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Abstract Conducting a vulnerability and risk assessment (VRA) is a critical step in adaptation planning and implementation. This research paper has assessed how the co-developed approach helped the Government of Nepal and stakeholders in Nepal to agree on and operationalize the vulnerability and risk assessment framework and what works best for the country's context. The methodological framework consists of eight steps including (i) scoping, (ii) reviewing the framework (iii) identifying data sources (iv) exploring data sources, nature, and character (v) data collection, tabulation, filtration, and normalization (vi) weightage and composite value (vii) analysis of the data (viii) identifying climate change impact, vulnerability, and risk. The output of the vulnerability and risk assessment in Nepal presents a compilation of impacts, vulnerabilities, and risks and a description of their context, root causes, and trends. These research-based assessment can be used to draw some possible adaptation options and improved decision-making at the national and sub-national levels. However, there were some challenges faced in analyzing the vulnerability and risks based on the indicators. There was a lack of a multi-year, complete, and uniform database, and difficulties in developing scenarios of hazards due to unclarity on climate change attribution. The lessons from this paper will be important for designing a more practical and country-driven VRA framework and methodology for other countries.

Keywords Assessment · Climate change · Framework · Indicators · Risk · Vulnerability

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Introduction

Climate change has become one of the most urgent environmental challenges in the twenty-first century as it possesses various challenges to people's livelihood, ecosystem, and other systems (Ma et al., 2017). In recent decades, climate change has impacted

natural and human systems in all socio-economic sectors across ecological regions and geographic areas (Baker et al., 2012; Shi, 2018; Tol, 2020). The strongest and the most comprehensive changes can be found in natural systems. Some impacts on human systems have also been attributed to varying degrees of climate change (IPCC, 2014). Nepal is considered one of the most risk countries, ranking tenth in terms of climate risk in Germanwatch Global Climate Risk Index 2021 (Eckstein et al., 2021). The profound impacts of climate change are severe due to the country's diverse topography and corresponding climatic variations, natural resource-based livelihoods, and resource constraints to manage the climate change impacts from climate extremes, hazards, and disasters (Rasul et al., 2020). The climatic impacts, losses, and damages resulting from it are unprecedented (MoFE, 2017; Rasul et al., 2020; Regmi et al., 2010; Shrestha & Aryal, 2011).

With the increasing impacts of climate change, it is essential to understand the climatic vulnerability and the risk to plan and minimize the future impacts. The vulnerability and risk assessment (VRA) helps in identifying and assessing risk across regions and sectors and is recognized globally as a critical step in adaptation planning and implementation (IPCC, 2014). It is also strongly reflected in Element B of the Least Developed Countries Expert Group (LEG) Guidelines (UNFCCC/LEG, 2012). Assessing human vulnerability to climate change requires knowledge of underlying natural (biosphere, hydrosphere, geosphere) and human made attributes (socio economic and demographic characters) and the linkages among them (Penn et al., 2016). Research on climate change impacts, adaptation, and vulnerability has sought to improve our understanding of the adaptation challenge by examining how physical changes in the environment translate to affect the adaptation practices carried out by the people (Fawcett et al., 2017). Without a systematic assessment of climate vulnerability and risk, the identification of adaptation plans, and their implementation is a challenge. Climate change adaptation efforts drawn based on VRA aim to address the implications or risks of potential changes in the frequency, intensity, and duration of weather and climate events that affect human and natural systems. The vulnerability and other risk assessments have improved our understanding of climate change, but due to their limitation in capturing temporal vulnerability and adaptation processes, it has caused limited efficacy of the adaptation interventions (Archer et al., 2017; Bennett et al., 2016).

A focus on climate change risk supports decision-making in the context of climate change. An approach based on risk provides a framework for utilizing information on the full range of outcomes, including events with low probability/high impact. Risk is not only determined by climate and weather events but also by the exposure and vulnerability of the human and natural systems to these events (IPCC, 2014a). To reduce risk effectively, it is essential to understand how the vulnerability is generated, how it increases, and how it builds up (O'Brien et al., 2004). Vulnerability describes a set of conditions among people that derive from both historical and prevailing cultural, social, environmental, political, and economic contexts. In this sense, vulnerable groups are not only at risk because they are exposed to a hazard, but also because of marginality, everyday patterns of social interaction and organization, and access to resources (Morrow, 1999; Watts & Bohle, 1993). Thus, the effects of a disaster on any household, community, or system result from a complex set of drivers and interacting conditions. Poor, marginalized, indigenous community, children, elderly, and women are among most vulnerable group and hard hit by climate change. Adhering to this, vulnerability and risk assessment has contributed to identifying adaptation deficits, selection of vulnerable and at-risk geographical areas, physiographic regions, municipalities, and populations, and adaptation planning and decision-making for vulnerable groups, communities, and ecosystems for Nepal.

This article aims to set standard methodology to identify indicator-based system of vulnerability and risk assessment. Article uses indicator-based approach to assess the vulnerability and the risk of the system. The process has considered cross-sectoral connections as well as the flow of data and information. As per IPCC AR5 and AR6, vulnerability is considered as the function of the sensitivity and the adaptive capacity of a system, whereas the risk in considered to be the function of the hazard, exposure, and vulnerability. Furthermore, the vulnerability and risk assessment is a iterative and dynamic process; thus, the findings and the suggested adaptation options may change over time and situation.

Fig. 1 Steps for vulnerability and risk assessment
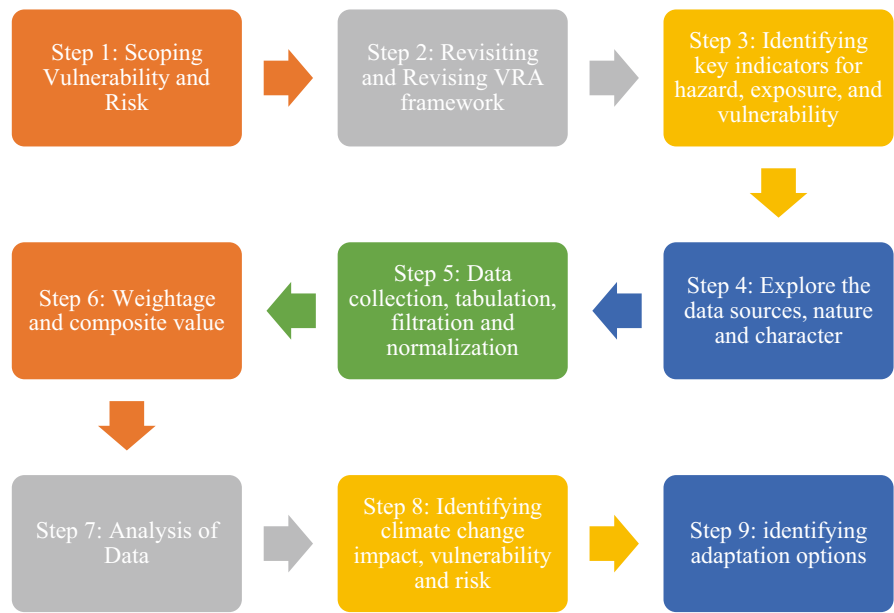
Methods

The VRA process, adopted in Nepal, is co-developed by the Government of Nepal, international and national non-government organizations, and civil society organizations. Co-developing projects and co-producing knowledge in scientific research and environmental management is not new. There have been many successful initiatives, for example, in ecosystem management in the Arctic (Robards et al., 2018), charismatic species research, small-scale coastal fisheries, and co-management (Kuperan & Abdulla, 1994).

This process incorporates methodological steps (Fig. 1) to assess climate change impact and risk in all eight thematic sectors and one cross-cutting sector identified by the Nepal's National Climate Change Policy 2019.[1] These steps have provided a comprehensive picture on identifying current and future climate vulnerabilities and risks and basis for identifying adaptation strategies for the National Adaptation Plan formulation process. For VRA, a mixed evaluation methodology (top-down and bottom-up) was used. The process has considered cross-sectoral connections as well as the flow of data and information. Various consultations including one to one, focused group discussion, were conducted with the representatives across sectors, cross-cutting regions, Thematic Working Groups (TWG)[2] from governmental and non-governmental organizations, Civil Society Organizations, Youth, women, Indigenous Peoples, and other related sectors to validate and make the process appropriate to all. Altogether over 20 discussions with the thematic working groups, seven provincial consultation, seven focused group discussion with the vulnerable communities, and over ten consultations with experts were conducted. The consultations helped to finalize the indicator, provide weightage, and validate the findings. The

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[1] Eight sectors specified in National Climate Change Policy 2019 include (1) Agriculture and Food Security; (2) Forests, Biodiversity and Watershed Conservation; (3) Water Resources and Energy; (4) Rural and Urban Habitats; (5) Industry, Transport and Physical Infrastructure; (6) Tourism, Natural and Cultural Heritage; (7) Health, Drinking Water and Sanitation; (8) Disaster Risk Reduction and Management and One cross-cutting sector include Gender and Social Inclusion, Livelihoods and Good Governance.

[2] Thematic Working Groups (TWG) were formed by the Government of Nepal that included sectoral experts from government and non-governmental organization. Altogether, nine TWGs were formed (eight for each of the eight sectors and one cross-cutting sector identified by the National Climate Change Policy) to provide technical assistance in the VRA development process.

overall process of indicator identification, data collection, analysis, and sharing was conducted over a span of 2 years (2019–2021). The following section focuses on the specifics of each phase in the VRA method.

Step 1: Scoping vulnerability and risk

The scoping exercise on vulnerability and risk assessment in different administrative boundaries, thematic and cross-cutting sectors, provinces, and physiographic regions[3] required an understanding of the context of (a) current climate conditions and scenarios, including slow onset and extreme events; (b) an assessment of potential impacts of climate extremes and climate change on potentially vulnerable sectors; and (c) an analysis of other underlying factors (biophysical, technical, and socio-economic factors) that can influence climate risks. The scoping of vulnerability and risk in the assessment units was a key starting point. The process of assessment was based on municipality and district-level data.

The assessment and analysis of climate trends and scenarios and climate-induced hazards were based on information and outputs of two published reports namely (a) Observed Climate Trend Analysis of Nepal (DHM, 2017) and (b) Climate Change Scenarios for Nepal (MoFE, 2019a, 2019b). Furthermore, the VRA conducted an analytical assessment of the socio-economic conditions, sectoral impact, risks, and vulnerability based on available literature and consultations with stakeholders. Moreover, for some socio-economic indicators with sufficiently long historical data, both the Mann–Kendall test and Sen's slope were employed to analyze the trend, its magnitude, and its significance of the trend.[4] MS-Excel program Version 1.0 was used to estimate the magnitude and significance of the trend.[5]

Step 2: Revisiting and refining the VRA framework

In 2017, the GoN published the Vulnerability and Risk Assessment framework and indicators for the National Adaptation Plan (NAP) formulation process. The assessment of national vulnerability and risk has adopted the same national framework, which is based on the Intergovernmental Panel on Climate Change (IPCC)-the fifth Assessment Report (AR5) and Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX).

The national framework, published by the then Ministry of Population and Environment (MoPE) in 2017 and revised in 2021 by the Ministry of Forests and Environment (MoFE), unpacks the elements of risk and customizes them as per the needs and applicability of the national context. The framework assumes that the risk of climate-related impacts results from the interaction of climate-related hazards (including climate extreme events) with the exposure and vulnerability of human and natural systems. The changes in the climate system (trends and scenarios), biophysical system, and socio-economic processes (including governance and adaptation and mitigation actions) are drivers of hazards, exposure, and vulnerability (IPCC, 2014). The national-level vulnerability and risk analysis are based on measurable and quantifiable available data, both primary and secondary. Following upon the GoN conceptual framework (Fig. 2) and based on Eq. (3) and Eq. (4) below, the methodological framework has been made clearer.

Step 3: Identifying key indicators for hazard, exposure, and vulnerability for different thematic and cross-cutting areas

In this step, the most relevant indicators[6] to thematic and cross-cutting areas to measure and assess trends in climatic hazards/stressors, exposure elements, state of sensitivity, and adaptive capacity were listed. The identification, shortlisting, and the finalization of the indicators were done based on the

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[3] High Mountain, Middle Mountain, Hill, Siwalik/Chure, and Tarai.

[4] The M-Kendall test is a non-parametric method that evaluates the significance of monotonic positive or negative trends based on historical data, while Sens's slope estimates the magnitude of the linear trend.

[5] MS-Excel template of the Mann–Kendall test available at https://help.xlstat.com/s/article/mann-kendall-trend-test-in-excel-tutorial?language=en_US Accessed 21st of March 2021.

[6] Indicators are parameters which provide information about specific states or condition which are nod directly measurable (Meyer, 2011). The purpose of use of indicators is to this quantified information to compare against critical thresholds or previous measurements.
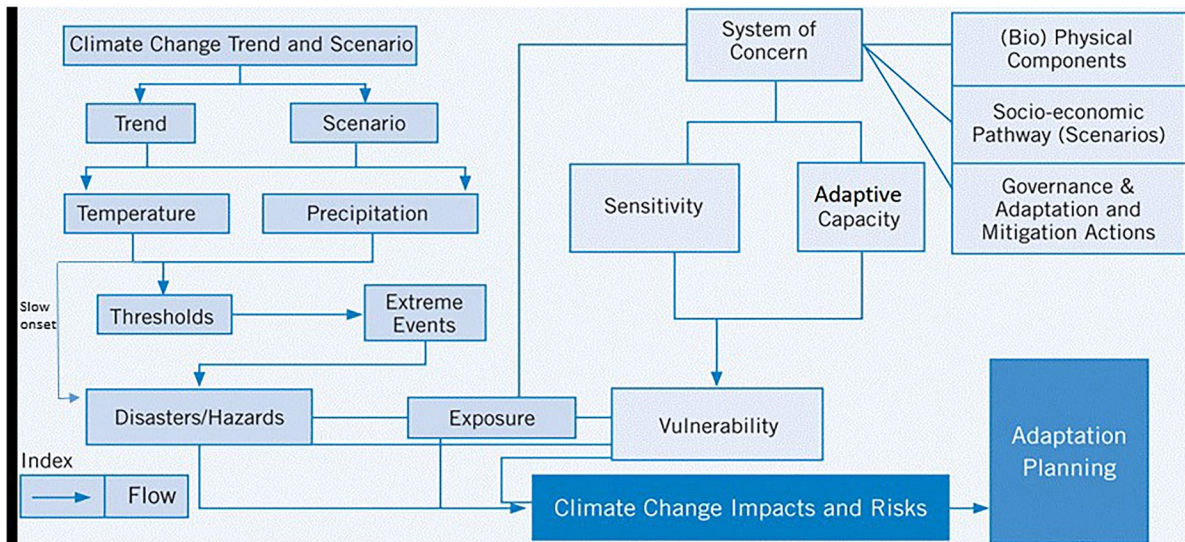
Fig. 2 Climate change vulnerability and risk assessment framework. Source: MoFE, 2021

discussion with Thematic Working Group (formed by the Government of Nepal) and the expert team. The indicators were used to measure and assess trends in hazards, exposure elements, state of sensitivity, and adaptive capacity of people and systems. Besides, the indicators were used for both quantifying and qualifying the extent, trends, and scenarios of the assessment units. SMART indicators[7] were identified based on literature review, review of previously published VRA framework, and stocking documents (MoPE, 2017). The indicators for climate variables and extreme events is listed in Table 1. Further few indicators of exposure, sensitivity, and adaptive capacity are discussed below.

Few examples of hazard indicators:

Few examples of exposure indicators.

- Human population: population size, number of households
- Animal and wildlife population: livestock population—dairy cattle, goat, sheep, pig, poultry, duck, fish; wildlife population

Table 1 Indicators for climate variable and climate extreme indices

Climate variables and extreme indices	Indicators
Temperature	Change in temperature (°C)
Precipitation	Change in precipitation (%)
Very wet days (P95)	Change in very wet days (%)
Extreme wet days (P99)	Change in extreme wet days (%)
Consecutive wet days	Change in consecutive wet days (%)
Number of rainy days	Change in number of rainy days (%)
Consecutive dry days	Change in consecutive dry days (%)
Warm days	Change in warm days (%)
Warm nights	Change in warm nights (%)
Warm spell duration	Change in warm spell duration (%)
Cold days	Change in cold days (%)
Cold nights	Change in cold nights (%)
Cold spell duration	Change in cold spell duration (%)

Few examples of sensitivity indicators.

- Demographic characteristics: gender (male and female); urban and rural population, age group (children, elderly, youth, adult), population density, economic status (poor, rich)

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[7] SMART Indicators refer to Smart, Measurable, Achievable, Relevant and Time-bound Indicators.

- Socio-economic characteristics: population growth, population density, sex ratio, *Dalit*[8] and Indigenous Peoples (*Janajati*)[9], differently abled, and people with health issues, poverty incidences, female household population, smallholder farmers, landless population, refugees, slum dwellers, orphans, the dependency ratio
- Characteristics of infrastructures: types of infrastructures, age of infrastructures, location of infrastructures (proximity to hazards), build-up and types, etc.
- Biophysical factors: soil types, topography, the trend of change in land use, and land cover
- Intrinsic characters: forest types, slope, landslide, and flood intensity
- Disturbance regimes: forest fire, invasive alien plants, degradation, and fragility status, pest, and diseases susceptibility
- Others: drainage density, sedimentation yield, demand, and supply

Few examples of adaptive capacity indicators.

- Socio-economic capability: Human Development Index (HDI), Gross National Income (GNI), Gross Domestic Income (GDI), Gross Domestic Product (GDP), economically active population, land ownership by female
- Access to goods and services: access to roads, infrastructures, communication, technology, education, health facilities, seeds, and planting materials and fertilizers, households with radio and television, rescue, and rehabilitation centers, water purification, and refinement, standardized roads, and alternative means of transportation
- Access to technology: climate-smart and climate-resilient technologies, risk reduction and management technologies, water-efficient technologies, soil, and land management technologies, crop management technologies, early warning systems, bioengineering technologies, sustainable forest management, Agro advisories
- Access to finance: investments and allocations, budget, insurance, credit, and grants facilities

- Policy and institutions: law, policy, plans, number of active agencies working, networks and groups, reinforcement of building codes.
- Awareness and knowledge: local and Indigenous knowledge, knowledge on climate change, and response measures
- Human resources: skilled human resources in disaster risk reduction and management, skilled human resources in other areas
- Step 4: Exploring data sources, nature, and character

For this study, a variety of data sources were used. The Department of Hydrology and Meteorology (DHM) provided district-level seasonal and climate patterns data, while climate scenarios were obtained from MoFE/ICIMOD (2019b), along with data from several other regional and global centers. The Central Bureau of Statistics (CBS), Department of Survey (DoS), DHM, related Ministries, development organizations, and international organizations such as the International Center for Integrated Mountain Development (ICIMOD), United States Geological Survey, and others were the primary sources of secondary data. For all quantitative datasets, a metric measurement method was used.

Step 5: Data collection, tabulation, filtering, and normalization

The VRA was carried out using secondary data (spatial or non-spatial) obtained from published or unpublished sources. The information came mostly from government sources or those which were credited and acknowledged by the government. Interviews, one-on-one meetings, exploratory surveys, and consultations with experts and related stakeholders and individuals were also valuable data collection methods. Survey software and Google Forms were used for the questionnaire survey. Extraction of information was also accomplished by the use of other correspondence methods such as the telephone, Skype, and email. Consultations in all Seven provinces of Nepal and at the national level, as well as field visits to selected local governments, were used to verify the data and information from secondary sources. The filtering, cleaning, and normalization process was conducted to ensure the collected or tabulated data were correct, complete, relevant, unique, properly

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[8] *Dalits* are marginalized groups in Nepal, traditionally considered "untouchables.".

[9] *Janajatis* are the indigenous people of Nepal.

Table 2 Score for the importance of variable (Satty Scale)

Intensity of importance	Definition of important scale
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

formatted, and with a uniform unit. A min–max method was adopted to normalize the quantitative dataset. The method transforms the values between 0 and 1 by subtracting the minimum score and dividing it by the range of indicator values as shown in Eq. (1).

$$x_{norm_i} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{1}$$

where, x_{norm_i} is the normalized value for the indicator x_i is the value of indicator; x_{max} is the maximum value of the indicator; and x_{min} is the minimum value of the indicator.

Step 6: Weightage and composite value

Every normalized data was given weightage by using a pair-wise comparison (Uribe et al., 2014) as indicated in the analytical hierarchy process (AHP) model to prioritize the related decision indicators. A slight modification of AHP is done particularly to adjust the prioritization of a long list of indicators. Scores of importance/priorities were given to nine scales (Saaty Scale) (Saaty, 1984) as given in Table 2. For this, a set of questionnaires was administered to at least 10–15 respondents including members of the Thematic Working Group (TWG), experts representing the governments, I/NGOs, and the private sector. The respondents were requested to respond to each pair of criteria and rate one relative to the other on a scale from "equal importance" to "extremely important." Based on relative importance, a pairwise comparison matrix was developed which was later used to compute the weight of each indicator through the eigenvalue and eigenvector analysis. The composite

values were then calculated based on the computed weightage.

The individual judgments were converted into group judgments (for each one of the paired comparisons) using their geometrical average. A comparison of all pairs results in a so-called ratio matrix. The numerical weights were then determined by normalizing the eigenvector associated with the maximum eigenvalue of the ratio matrix. Then, through aggregated value, the index of exposure, sensitivity, and adaptive capacity was calculated by using the weighted linear summation method which is a linear combination of standardized values using weights as shown in Eq. (2).

$$AC = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where,

AC is an aggregated indicator, e.g., aggregated adaptive capacity, x_i is an individual indicator of the adaptive capacity of a vulnerability component, and w_i is the weight assigned to the corresponding indicator x_i. The preferred alternative is that with the minimum value of adaptive capacity.

Step 7: Analysis of data

After the calculation of the index of the adaptive capacity, sensitivity, exposure, and hazard (based on the Eq. 2), the indexes were then re-calculated to produced, vulnerability, and the risk (based on the Eq. (3) & (4)). The findings were then presented in a variety of ways, adaptive capacity, sensitivity, vulnerability, and risks. The analysis of data identified "climate-vulnerable/risk hotspots" as well "hazard hotspots." The maps were prepared for different units like districts, municipality, physiographic regions, and provinces by eight thematic sectors and one cross-cutting sector.

Step 8: Identifying climate change impacts, vulnerability, and risk

The vulnerability of the identified sub-sectors within a sector and the aggregate of these sub-sectors of each sector were analyzed with an aggregated value of sensitivity and adaptive capacity as shown in Eq. (3) and Fig. 2. According to IPCC-AR5, vulnerability is a function of sensitivity and adaptive

capacity. Figure 2 illustrates a typical process and analysis of the chain of vulnerability and risk with the indicator-wise data of sensitivity, adaptive capacity, and exposure.

$$V = S - AC \tag{3}$$

where,

V is the composite vulnerability indicator,

S is the sensitivity component of vulnerability and.

AC is the adaptation capacity component of vulnerability.

Similarly,

Sub-sector-wise and cumulative risk were estimated as a function of hazard intensity, exposure, and vulnerability as shown in Eq. (4).

$$R = H_{intensity} \times V \times E \tag{4}$$

where,

R is the risk index,

$H_{intensity}$ is the hazard intensity,

V is the vulnerability, and.

E is exposure.

The final risk was rescaled by dividing the outcome values by the maximum risk values of all administrative units as in Eq. (5).

$$scale = R/\max(R), R \in \{admin \ units\} \tag{5}$$

The climate change vulnerabilities and risks were ranked into five categories (very low, low, moderate, high, and very high) for their threats or impacts at the sectoral, provincial, physiographic region, and district levels by using the Jenks natural breaks (Jenks, 1967) method. The natural break classes are characterized based on the variety of data an indicator possesses; thus, the natural break value may differ with the dataset/indicators. The VRA created the classes in such a way that the best groups of similar values come together and maximize the differences between classes. The ranking was further validated through a consultative process with key stakeholders in all seven provinces of Nepal, sectoral ministries, Thematic Working Groups, group of experts, academia, I/NGO representatives, youths, and other stakeholders. From the analysis of data, maps and indices for existing climate trends and projected scenarios for climate hazards, vulnerabilities, and risks were generated.

Results

Climate change hazards in Nepal

Floods, landslides, epidemics, and fires are the major climate-related disasters in Nepal. This study considered 15 climate-related hazards that were recorded in disaster databases. These were floods, landslides, epidemics, fires, thunderbolts, heavy rainfall, droughts, glacial lake outburst floods (GLOFs), heatwaves, cold waves, windstorms, avalanches, snowstorms, hailstorms, and forest fires. Trend analysis of 14 climate-related hazards (except GLOFs) revealed that there is a significant increasing trend of hazard occurrences, especially after 1990. All hazard events are in increasing trends, except meteorological droughts which are in a decreasing trend. While trends of epidemics, avalanches, hailstorms, and droughts were statistically insignificant, the trends of the other ten hazards were statistically significant at a 5% level.

Based on the analysis of historical hazard occurrences, Sunsari, Kailali, Morang, Jhapa, Rautahat, Bardiya, Sarlahi, and Saptari districts were identified as "Flood Hazard Hotspots." Similarly, Dhading, Sankhuwasabha, Baglung, Sindhupalchok, Dolpa, Taplejung, Rolpa, Makawanpur, Myagdi, Lamjung, Dolakha, Nuwakot, Gorkha, Solukhumbu, Kavrepalanchok, Dailekh, Darchula, Syangja, Palpa, Khotang, Bajura, Kalikot, Kaski, Jajarkot, Bajhang, Gulmi, and Ilam districts were identified as "Landslide Hazard Hotspots." Lastly, based on human and economic impacts, Makawanpur, Rautahat, Banke, Kailali, Siraha, Morang, Doti, Chitawan, Dhanusha, Sarlahi, Mahottari, Parsa, Saptari, Sunsari, Sindhupalchok, Dang, Kaski, Kanchanpur, and Jhapa districts were identified as the climate-related "Disaster Hotspots." Knowing these hotspots can support in devising anticipatory risk management measures, as well as adaptation and resilience-building strategies/initiatives targeted to vulnerable populations and sectors.

The climate change scenarios indicated that, across Nepal, temperature, warm days and nights, and warm spell duration are likely to increase in the future. Cold days and nights and cold spell duration are likely to decrease. Precipitation, very wet days, and extreme wet days are likely to increase, and rainy days are likely to decrease. An increase in consecutive dry days and an increase in consecutive wet days are about as likely as not.

Future scenarios of climatic hazards were inferred from the scenarios of climate variables and climate extreme indices. In the future, cold waves and snowstorms are likely to decrease. Heatwaves, heavy rainfalls, thunderbolts, windstorms, floods, landslides, GLOFs, fires, avalanches, epidemics, and forest fires are likely to increase. Increases in hailstorms and droughts are about as likely as not.

Exposure to climate change

In this assessment, exposure is defined as the presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by climate-induced hazards or climate extreme events. Exposure is also determined by the areas of land that are vulnerable to various climatic hazards or extreme events. Rupandehi and Kapilbastu, for example, have high to very high exposure. This is primarily because these two districts have more land under cereal crops than other Tarai districts. Another determinant of high exposure is exposure to infrastructure and resources. For example, Kathmandu, Kaski, and Morang districts are particularly exposed to climatic hazards due to their superior infrastructure and resources in comparison to other districts.

Climate change vulnerability in Nepal

In this assessment, vulnerability is defined as sensitivity or susceptibility to harm, as well as a lack of capacity to cope and adapt. It is influenced by a variety of conditions varying in their sensitivity, such as demographic, socio-economic, ecological, physical, and geological characteristics, as well as the status and condition of resources and infrastructures. Furthermore, it is dependent on adaptability, which is influenced by socio-economic assets, the existence of policy and regulations, access to power, and access, control and ownership over resources.

Climate change sensitivity

The exposed units' physical, biological, socio-economic, and structural characteristics differentiate sensitivity. A composite sensitivity index is generated in this assessment by combining all of the sectoral sensitivity values. The results show that all the hill and mountain districts of Lumbini, Karnali, and Sudurpaschim Provinces are highly sensitive to the effects of climate change. Only the mountain districts of the Province One have a high to very high level of sensitivity. Madhesh Province districts have a medium to very low level of sensitivity.

In terms of municipal sensitivity, the overall findings show that 121 municipalities spread across all seven Provinces have a high to a very high level of sensitivity. The municipalities are sensitive to climate change because of their geological features, such as slope, geology, and soil characteristics, which make them more sensitive to climate extreme events and hazards. Municipalities in the hilly and mountain regions are more sensitive than those in the Tarai region. However, some districts in the Tarai region (particularly in flood-prone municipalities) have a higher population density and infrastructure, making them more susceptible to annual flood events. Also, the findings for rural municipalities show that the majority of local governments in Tarai and mid-hill across all Provinces are highly sensitive to climate-induced extreme events and hazards.

Adaptive capacity of the country

Adaptive capacity is assessed based on the ability of systems, institutions, humans, and other organisms to adapt to potential damage, capitalize on opportunities, or respond to the consequences of climate change. According to the assessment, the districts of Lalitpur, Chitawan, Morang, Jhapa, and Kathmandu have a very high adaptive capacity and can adapt well to the adverse effects of climate change. These districts have higher HDI, GDP, and literacy rates, as well as better access to infrastructure, health, and other services. On the contrary, the majority of districts in Karnali Province and Sudurpaschim Province have a low adaptive capacity. In comparison to other Provinces, access to services, technologies, and infrastructure are limited in these provinces. The findings further show that the capacity to cope to adapt is limited and constrained due to socio-economic and technological limitations.

Findings for urban municipalities show that 40 municipalities are found to have high to very high adaptive capacity, while 179 municipalities have low to very low adaptive capacity. Older municipalities
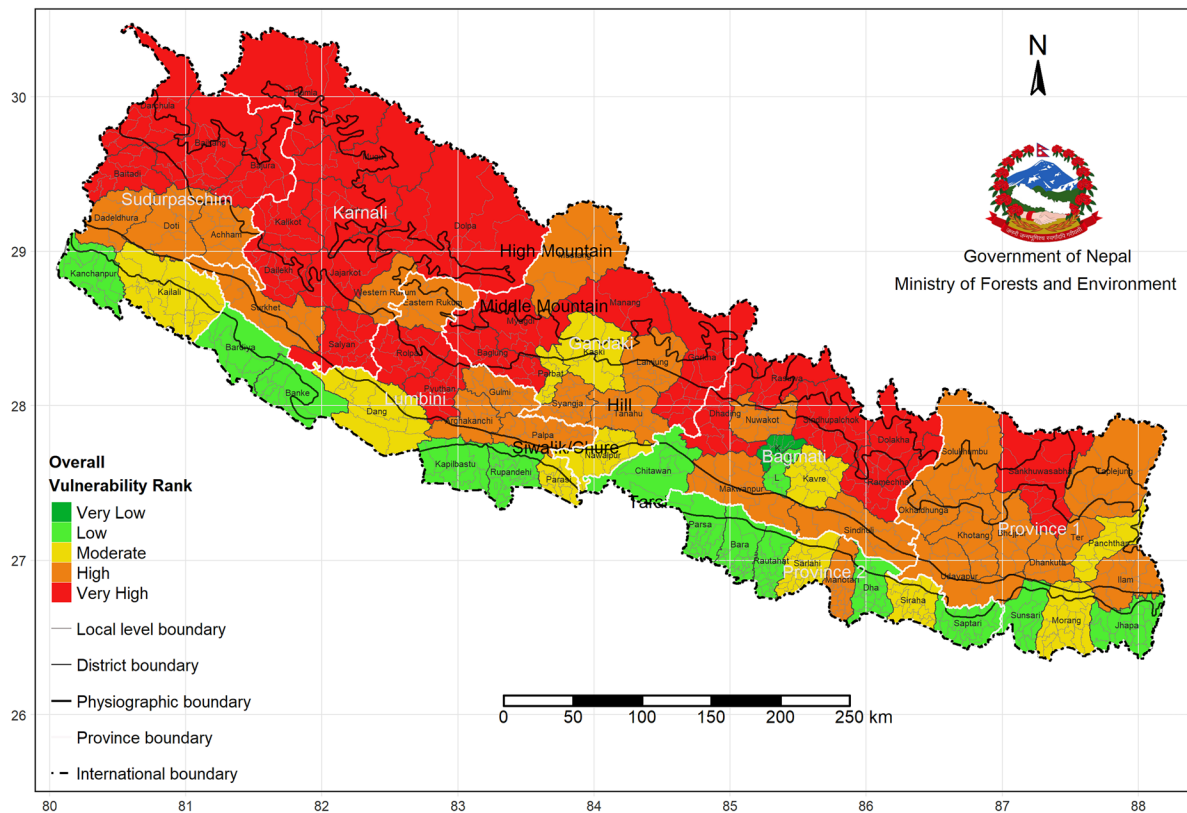
Fig. 3 Vulnerability map of Nepal. Source: MoFE (2021)

established before 2011 have greater adaptive capacity. In comparison to newly established/declared municipalities, these municipalities have made significant investments in urban planning and local development. Biratnagar, Birgunj, Damak, Kathmandu, Butwal, Itahari, Pokhara Lekhnath, and other municipalities have a high to very high adaptive capacity. Low adaptive capacity is primarily caused by a lack of access to resources and services, which includes a lower HDI and a higher incidence of poverty in the provinces and respective rural municipalities.

Vulnerability status of Nepal

The findings indicate that the majority of the districts (50) have a high to very high vulnerability level. Furthermore, the majority of these districts is located in hilly or mountainous terrain. Dhading, Rolpa, Humla, Mugu, Rasuwa, Myagdi, Dolakha, Sankhuwasabha, Baglung, Sindhupalchok, Gorkha, Dailekh, Pyuthan,

Darchula, Dolpa, Baitadi, Salyan, Manang, Bajura, Kalikot, Jajarkot, Jumla, Bajhang, and Ramechhap are among those. Furthermore, all-mountain districts are classified as highly vulnerable. Makawanpur, Lamjung, Dhankuta, Terhathum, Nuwakot, Western Rukum, Solukhumbu, Tanahu, Udayapur, Syangja, Surkhet, and Achham Arghakhanchi, Palpa, Bhojpur, Sindhuli, Mustang, Doti, Eastern Rukum, Khotang, Okhaldhunga, Taplejung, Mahottari, Gulmi, Dadeldhura, and Ilam are the high-vulnerability districts (Fig. 3 and Table 3).

The vulnerability in the Tarai appears moderate to low in the majority of districts because of high adaptive capacity and comparatively lower sensitivity. With the prevalence of multidimensional poverty and hazards, other factors such as remoteness, access to resources, and existing facilities influence vulnerability. It is also influenced by a variety of factors, including improved access to roads and infrastructure, diverse biodiversity, and access to energy. The capital, Kathmandu, has very low vulnerability due

Table 3 Overall vulnerability index of Nepal

Vulnerability rank	District
Very high (0.778–1)	Dhading, Rolpa, Humla, Mugu, Rasuwa, Myagdi, Dolakha, Sankhuwasabha, Baglung, Sindhupalchok, Gorkha, Dailekh, Pyuthan, Darchula, Dolpa, Baitadi, Salyan, Manang, Bajura, Kalikot, Jajarkot, Jumla, Bajhang, Ramechhap
High (0.623–0.777)	Makawanpur, Lamjung, Dhankuta, Terhathum, Nuwakot, Western Rukum, Solukhumbu, Tanahu, Udayapur, Syangja, Surkhet, Achham, Arghakhanchi, Palpa, Bhojpur, Sindhuli, Mustang, Doti, Eastern Rukum, Khotang, Okhaldhunga, Taplejung, Mahottari, Gulmi, Dadeldhura, Ilam
Moderate (0.502–0.622)	Kavrepalanchok, Parbat, Kailali, Siraha, Morang, Dang, Nawalpur, Kaski, Panchthar, Sarlahi, Parasi
Low (0.179–0.501)	Kapilbastu, Sunsari, Rautahat, Bardiya, Lalitpur, Bhaktapur, Banke, Rupandehi, Bara, Chitawan, Dhanusha, Kanchanpur, Jhapa, Parsa, Saptari
Very low (0–0.178)	Kathmandu

to their high adaptive capacity (e.g., easy access to resources and services) and low sensitivity (e.g., better inclusion and access).

Risk of climate change impact

Risk is determined by factors such as exposure, vulnerability, and hazards. The exposure and vulnerability in this study are based on the current context, while the hazard is based on climate extreme events in the mid-term (2030) and long-term (2050) periods under two climatic scenarios, RCP 4.5, and RCP 8.5. As a result, the overall risk scenarios are dependent on the hazard scenario. The function of climate extreme events is a hazard. Floods, for example, are affected by precipitation, wet spell duration, and the number of extreme wet days; similarly, landslides are affected by precipitation and the number of extreme wet days, and hailstorms are affected by temperature and precipitation.

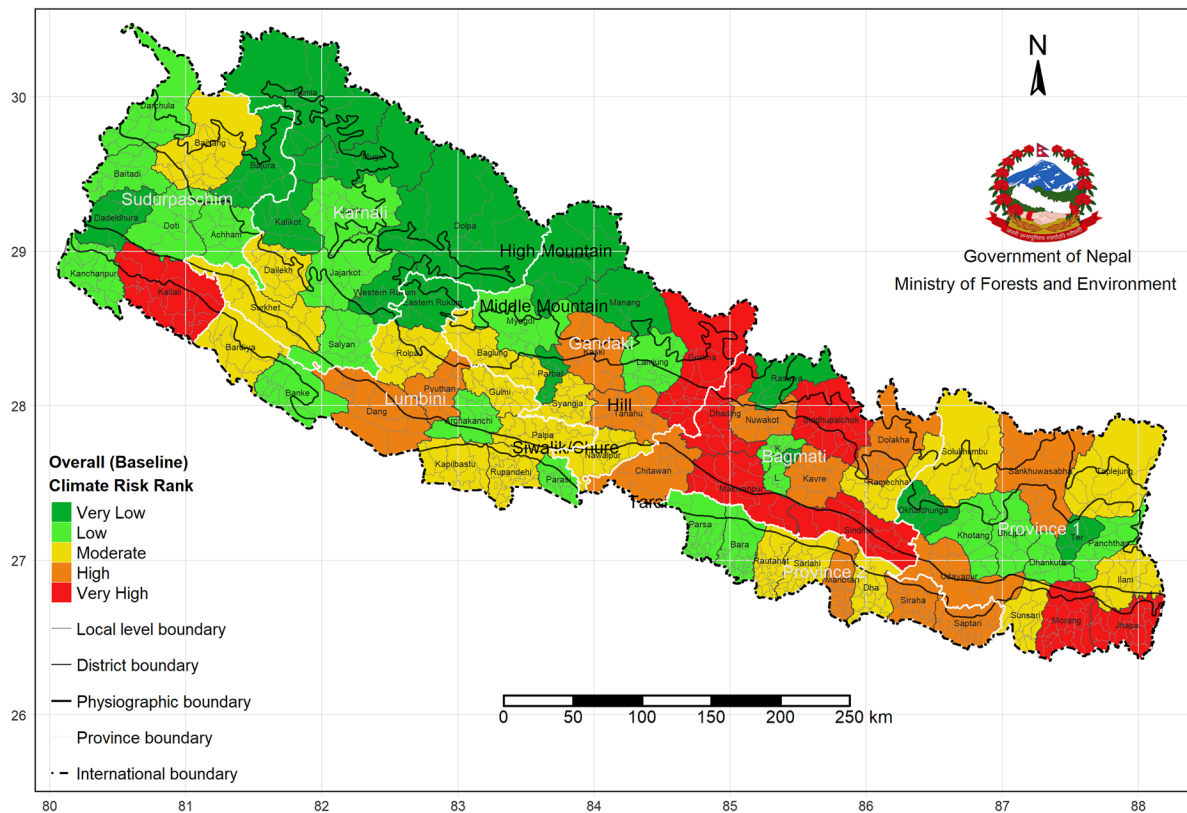*Baseline risk of climate change impact*

The overall baseline risk of climate change impact is calculated by taking current hazards, exposure, and vulnerability into account. Since it is an aggregated risk index and map, it may not accurately represent sector-specific baseline risks. According to the findings, climate-induced disasters had a significant impact on Dhading, Makawanpur, Sindhupalchok, Gorkha, Kailali, Sindhuli, Morang, and Jhapa Districts. Furthermore, climate-induced disasters had a significant impact on Dolakha, Nuwakot, Sankhuwasabha, Tanahu, Kavrepalanchok, Udayapur, Pyuthan,

Siraha, Chitawan, Dang, Kaski, Mahottari, and Saptari Districts (Fig. 4).

On the other hand, disasters have had a comparatively lesser effect in Humla, Mugu, Rasuwa, Terhathum, Western Rukum, Bhaktapur, Parbat, Dolpa, Mustang, Manang, Eastern Rukum, Okhaldhunga, Bajura, Kalikot, and Dadeldhura Districts. Myagdi, Lamjung, Dhankuta, Lalitpur, Darchula, Banke, Achham, Arghakhanchi, Baitadi, Bhojpur, Salyan, Bara, Doti, Khotang, Kanchanpur, Panchthar, Jajarkot, Jumla, Parasi, Parsa, and Kathmandu were among the districts which experienced comparatively little damage from disasters. Despite their high vulnerability, Humla, Mugu, Dolpa, Manang, and Bajhang currently face a low risk and impact from climate change indicated in Table 4. It is mostly because climate severe events occur infrequently in these districts. Furthermore, despite witnessing low to very low vulnerability, the districts of Jhapa, Chitawan, Rupendehi, Kapilvastu, and Kathmandu are at higher risk due to their higher climate extreme events and high exposure. In case of Kathmandu, despite having very low vulnerability, the high exposure puts it at higher climate risk. For example, Kathmandu was the hotspot of COVID-19 risk in Nepal because Kathmandu has higher demographic exposure (population of 1,744,240 which is five times higher than the average district population in Nepal).

Projected risks of climate change impact in the short term (2030)

Under RCP 4.5 in 2030, fifteen districts fall in the very high-risk category while seventeen districts fall in the high-risk category. Except for some exceptions

Fig. 4 Baseline risk of climate change impact in Nepal (MoFE, 2021)

under RCP 4.5, all districts in the Tarai, mid-hills, and mountains fall under high-very high risks. Likewise, under RCP 8.5 in 2030, nineteen districts fall in the very high-risk category while seventeen districts fall in the high-risk category. Most districts in Koshi Province (Province One), Madhesh Province, Bagmati Province, Gandaki Province, and Lumbini Province fall in a high-risk category under both RCP scenarios. The Karnali and Sudurpaschim Provinces seem to be at low risk under both scenarios in 2030. Most of the southern districts of Madhesh Province and Province One are likely to experience a high risk of climate change (Fig. 5).

Projected risks of climate change impact in long term (2050)

More districts and Provinces will be at high risk under both scenarios in 2050. Under RCP 4.5 in 2050, nineteen districts fall in the very high-risk category while twenty-one districts fall in the high-risk category. Meanwhile, thirty-three districts fall in the very high-risk category, and sixteen districts in the high-risk category. Additionally, twelve districts were added to the high-risk category in RCP 8.5 compared to RCP 4.5. Most of the districts of Province One, Madhesh Province, Bagmati Province, Gandaki Province, and Lumbini Province will have high to very high degree of risks. Compared to the medium term (2030), the climate risk will increase in the long term (2050) in Lumbini, Karnali, and Sudurpaschim Provinces. Climate extreme events are projected to increase rapidly in 2030 and 2050 which will have an overall impact on the status of risk in the provinces. However, the vulnerability might change in the future due to demographic, socio-economic, and ecological changes which might contribute to either increased or decreased risks in the districts and Provinces. Looking at the current trends, the future risks is likely to increase in future (Fig. 6).

Table 4 Districts with high extreme events, exposure, and vulnerability

Elements of risks	High-very high	Low-very low
Climate extreme events	*Very high*: Sankhuwasabha, Morang, Chitawan, Jhapa *High*: Dhading, Makawanpur, Sunsari, Rautahat, Sindhupalchok, Tanahu, Kavrepalanchok, Parbat, Syangja, Kailali, Siraha, Rupandehi, Palpa, Sindhuli, Bara, Dhanusha, Nawalpur, Kaski, Taplejung, Panchthar, Sarlahi, Mahottari, Parasi, Parsa, Saptari, Ilam	*Very low*: Humla, Mugu, Dolpa, Mustang, Manang, Bajura *Low*: Rolpa, Rasuwa, Myagdi, Western Rukum, Dailekh, Darchula, Baitadi, Salyan, Eastern Rukum, Kalikot, Jajarkot, Jumla, Bajhang, Dadeldhura
Exposure	*Very high*: Kapilbastu, Kailali, Rupandehi, Morang, Kathmandu *High*: Sunsari, Gorkha, Kavrepalanchok, Sindhuli, Bara, Chitawan, Dang, Kaski, Jhapa, Saptari	*Very Low*: Mugu, Rasuwa, Dhankuta, Terhathum, Western Rukum, Parbat, Salyan, Manang, Eastern Rukum, Okhaldhunga, Bajura, Kalikot, Jajarkot, Jumla, Dadeldhura *Low*: Rolpa, Humla, Myagdi, Lamjung, Nuwakot, Sankhuwasabha, Baglung, Solukhumbu, Dailekh, Bhaktapur, Darchula, Syangja, Dolpa, Achham, Arghakhanchi, Baitadi, Bhojpur, Doti, Khotang, Taplejung, Panchthar, Parasi, Ramechhap
Vulnerability	*Very high*: Dhading, Rolpa, Humla, Mugu, Rasuwa, Myagdi, Dolakha, Sankhuwasabha, Baglung, Sindhupalchok, Gorkha, Dailekh, Pyuthan, Darchula, Dolpa, Baitadi, Salyan, Manang, Bajura, Kalikot, Jajarkot, Jumla, Bajhang, Ramechhap *High*: Makawanpur, Lamjung, Dhankuta, Terhathum, Nuwakot, Western Rukum, Solukhumbu, Tanahu, Udayapur, Syangja, Surkhet, Achham, Arghakhanchi, Palpa, Bhojpur, Sindhuli, Mustang, Doti, Eastern Rukum, Khotang, Okhaldhunga, Taplejung, Mahottari, Gulmi, Dadeldhura, Ilam	*Very low:* Kathmandu *Low*: Kapilbastu, Sunsari, Rautahat, Bardiya, Lalitpur, Bhaktapur, Banke, Rupandehi, Bara, Chitawan, Dhanusha, Kanchanpur, Jhapa, Parsa, Saptari

Discussion

The VRA framework and methodology used in this paper to assess climate change impacts is a significant step toward decision-making particularly helping the policymakers and practitioners to identify and prioritize the appropriate adaptation options as per the degree of urgency of risks and vulnerability.

The vulnerability and risk assessment framework and methodology based on the set of indicators demonstrate both opportunities and challenges in categorizing the geographical areas. The indicator-based approach heavily relies on data and information available at various scales. In absence of the data, the analysis becomes challenging. Also, the indicator-based approach is assumption based and relies on the expert's perception of which indicator might represent the sensitivity and adaptive capacity.

Agriculture, water, disaster management, energy, biodiversity, health, urban planning, and livelihoods are all expected to be impacted by the risk scenarios.

However, there are some unknowns. A higher level of uncertainty exists in the models due to uncertainty in future socio-economic pathways and climatic attribution. As a result, the findings of this assessment should be regarded as indicative rather than absolute. Having said that, the study's preliminary findings capture a wide range of future climate variability and are extremely useful in assisting policymakers in developing appropriate strategies for reducing the risk and vulnerability for the years to come to consider underlying uncertainties while designing risk reduction measures.

In terms of process, the methodology development and testing have been very useful in terms of forging strong collaboration between government and nongovernment actors. The co-development of the methodology has contributed to harnessing knowledge exchange, sharing of resources and expertise, and building consensus on a more practical and feasible approach to vulnerability and risk assessment.
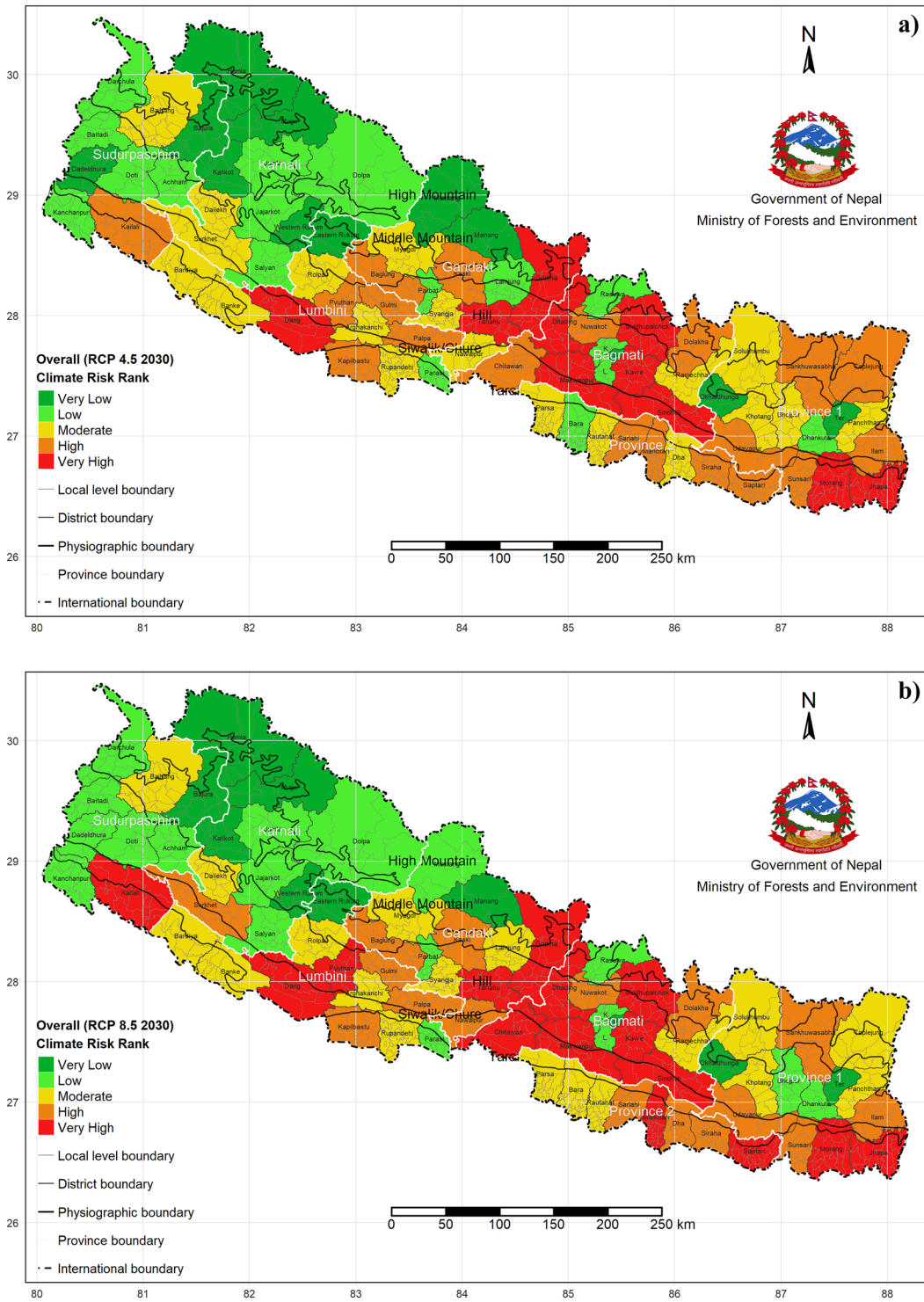
Source: MoFE (2021)

Fig. 5 Risk scenarios of Nepal **a** RCP 4.5 2030; **b** RCP 8.5 2030. Source: MoFE (2021)
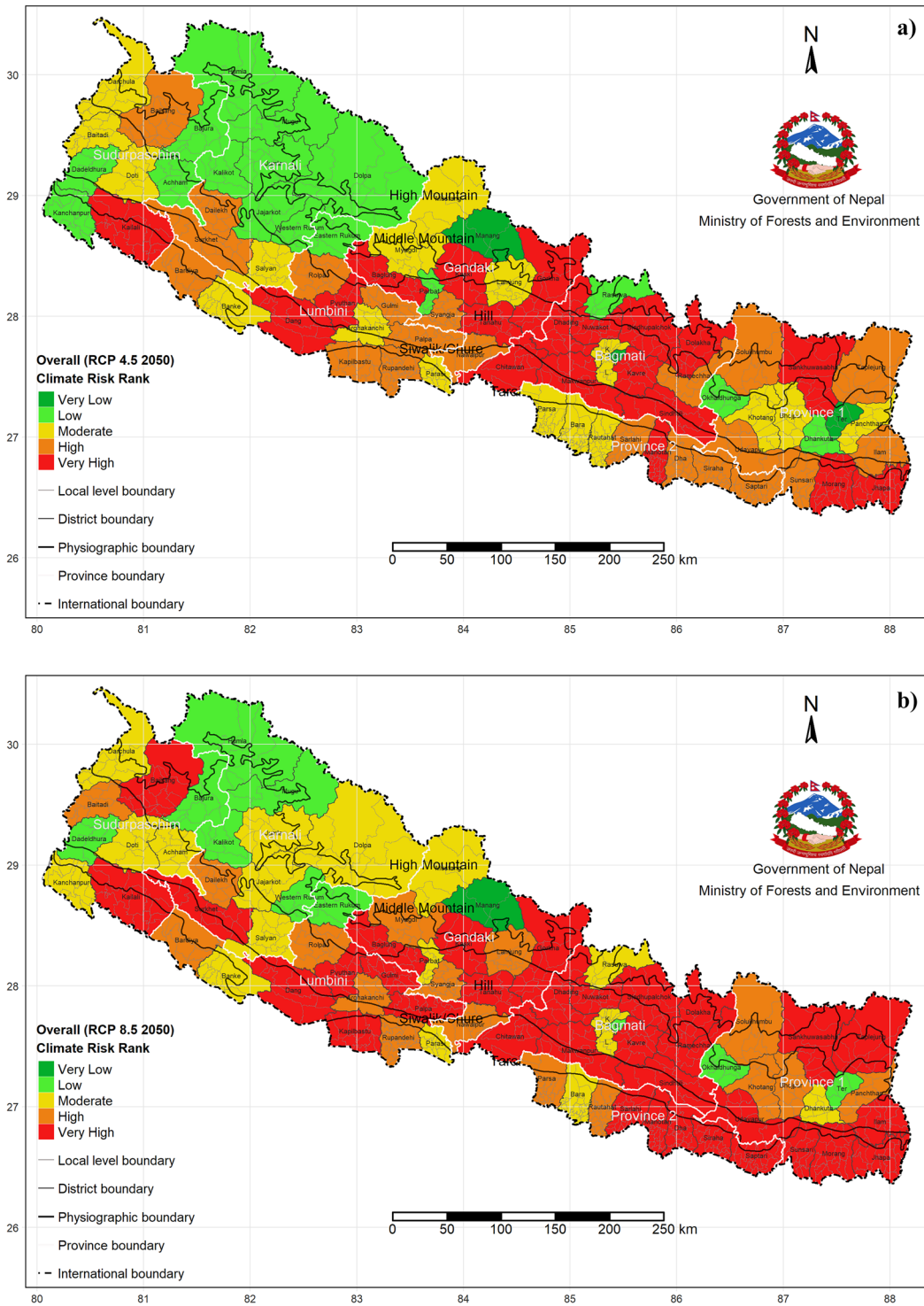
Source: MoFE (2021)

Fig. 6 Risk of climate change impact scenarios in Nepal **a** RCP 4.5 2050; **b** RCP 8.5 2050. Source: MoFE (2021)

Conclusions

Conducting the vulnerability and risk assessment is a critical step in adaptation planning and implementation. The potential uses of the VRA could be multi-fold. This approach is an opportunity not only to enhance the country's knowledge but also to promote a co-development process that binds and promotes collaboration among stakeholders for agreeing to what works best for the country's context. The output of the vulnerability and risk assessment is a compilation of impacts, vulnerabilities, and risks and a description of their context, root causes, trends, and potential assumptions made. This will facilitate further analysis required for the ranking of vulnerabilities, and the identification and prioritization of adaptation options. In Nepal, the vulnerability and risk assessment work has contributed to establishing a strong baseline for adaptation planning and decision-making as it has been used by the government, the developmental partners, and the community-based organizations to plan and prepare for climate actions. The adaptation options developed from the VRA will also help to ensure the inclusion and prioritization of vulnerable, socially excluded or marginalized group, people of different gender and age.

However, there were some challenges faced in assessing indicator based vulnerability and risks. Non-uniformity in data, lack of temporal/spatial data, and incomplete data affected the indicator finalization process; few indicators was even dropped due to the same reason. There were also difficulties in developing scenarios of hazards due to uncertainty related to climate change attribution. The vulnerability and the risk assessment are the dynamic process, so the institution/individual assessing the same needs to consider this and timely update the process. These lessons can be important designing a more practical and country-driven VRA framework and methodology for other countries.

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