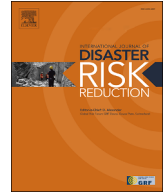


Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdr

Ecosystem restoration reduces community vulnerability to water-induced disasters: Need to rethink Chure conservation in Nepal

Prakash K. Paudel ^{a, *}, Arjun Lamichhane ^a, Krishna Prasad Acharya ^b, Rabin Bastola ^{c, d}

^a Center for Conservation Biology, Kathmandu Institute of Applied Sciences, Kathmandu, Nepal

^b Society for Conservation Biology Nepal, Kathmandu, Nepal

^c Department of Environmental Science, Amrit Campus, Tribhuvan University, Kathmandu, Nepal

^d Water Engineering and Management, Asian Institute of Technology, Pathum Thani, Thailand

ARTICLE INFO

Keywords:

Chure
Disaster
Restoration
Vulnerability
Ecosystem-based disaster risk reduction
Nature-based solution
Ecosystem services

ABSTRACT

Disaster risk reduction strategies are often accompanied by conventional adaptation approaches, involving high costs and limited flexibility. Conversely, ecosystem-based adaptation (EbA) has been advocated as a sustainable approach because it is cost-effective, efficient and provides co-benefits (e.g., ecosystem services). However, there is limited awareness and understanding among both disaster risk reduction professionals and ecologists about the linkages of ecosystem restoration to disaster risk reduction. Here, we assessed people's perceptions towards the availability of ecosystem services in the highly degraded and fragile landscape to floods and soil erosion in Central Nepal. We then assessed vulnerabilities at household level in both pre- and post-restoration periods, using indicators such as distance to the river, land cover composition (ratio of forest to non-forest), occupation, availability of ecosystem services, and effectiveness of the restoration projects in the vicinity. Our results show that vulnerability as a function of adaptive capacity and sensitivity decreased even though there were no significant improvements in some of the provisions of ecosystem services we assessed. Since our results showed restoration projects were not integrated following the principles of EbA criteria, careful integration during project design and implementation would strengthen community resilience in future. Our work provides new insight into the restoration response to disasters and provides a basis for future research and policy development.

1. Introduction

The Chure—also known as Siwalik or Churia—represents one of the most important regions rendering critical ecosystems in the Himalayas [1]. It covers 12.76% total area of Nepal and is situated between the lower part of the mid-hills and the upper part of the Gangetic floodplain [2]. Chure is predominantly composed of sandstone, mudstone and shale, which weather—at different rates—resulting formation of porous soil of alluvial and colluvial deposits [3,4]. Such a geologically fragile landscape, however, is under extreme human pressure for lands (e.g., agricultural land, human settlement) [5], infrastructure development [6], mining of sands/boulders [7] and extraction of firewood and timber [6]. Such anthropogenic pressures combined with extreme rains, earthquakes, and porous geology have made the Chure region highly vulnerable to various hazards such as floods, soil erosion and landslides [8]. Churia forest covers 23.04% of a total 5.96 million ha forest area in Nepal, and is highly disturbed in terms of grazing, forest fire, landslide and bush cutting [9]. Chure is a crucial landscape for Nepal's ecological and socio-economic sustainability [10]. It provides

* Corresponding author.

E-mail address: pk.paudel@gmail.com (P.K. Paudel).

critical ecosystem services, notably, regulating surface water flows and recharging groundwater — a main source of water for more than 14 million people inhabiting the downstream Terai plains [11]. With the clearance of the majority of forest areas in the Terai—a highly fertile flat area south of Chure—over the last century, the Chure hills are now the primary source of timber, fuelwood, fodder and other forest products for not only communities living in the Chure hills but also for downstream communities in the Terai-Madhesh region [12]. The Government of Nepal (GoN) established the President Chure-Terai Madhesh Conservation Development Board in 2014 for the restoration, conservation and management of the vulnerable landscape of Chure, Terai and Madhesh [13]. The board has been carrying out several activities ranging from construction of check dams and spurs to afforestation for fixing erosion, sedimentation and floods. There is a preponderance of hard grey solutions (e.g., embankment, retention wall etc.) [14]. Such 'grey' solutions are easy and quick to implement and are effective in mitigating the immediate effects of a disaster [15,16]. However, such approach has been criticized for their huge capital demand and environmental costs, and there are calls to integrate ecosystem-based adaptation to disaster risk reduction because they are often capital friendly (e.g., low investment and maintenance cost) and effective to control disaster risk [15,17–20].

Ecosystem-based disaster risk reduction (Eco-DRR) is “sustainable management, conservation and restoration of ecosystems to reduce disaster risk, to achieve sustainable and resilient development” [19]. Thus, there is a growing consensus that high and undisturbed biodiversity renders a greater extent of ecosystem processes and services [21,22], and supports ecosystem-based adaptation [23]. It is considered a branch of the broader nature-based solutions (NbS) [24]. NbS rather focuses on solutions based on ecosystems to address challenges posed by climate change and disasters and involves restoration of the ecosystems, and maintaining biodiversity and natural habitats [24]. Hazards such as floods and soil erosion cause the degradation of ecosystems [25]. Thus, the restoration of healthy and functional ecosystems helps to reduce climate change vulnerability and disaster risk [26], and at the same time contributes to sustaining human livelihoods by providing essential goods such as food, fiber, medicines and construction materials.

The low-income households with subsistence livelihoods suffer the most from disasters [27]. This is true for Nepal where a high proportion of people make their livelihoods through subsistence agriculture in this geologically fragile country [28]. Here, the effectiveness of any engineered structures (e.g., concrete dam, river embankments) depends not only on how well they reduce hazards but also on how well they promote ecosystem restoration. This is because ecosystem restoration not only provides critical resources for sustaining community livelihoods but also attenuates the impacts of hazards by providing regulating ecosystem services [25].

In this study, we focus on water-induced hazards, namely, flood, erosion and sedimentation, that co-occur and evolve simultaneously as soon as rainfall starts [29]. Since Chure has a highly fragile geology and steep slope gradient, these hazards are the results of human-environment interaction where vegetation in the landscape has a crucial role. A well-managed and natural forest landscape with mixed vegetation and ground cover promotes water infiltration underground, reduces the discharge rate and intensity of water flow and provides mechanical support against erosion capacity of flood and water run-off [30–32]. A better-designed restoration project promotes such an ecological process in the long term [24,31,33,34]. Thus, this study attempts to determine household vulnerability to water-induced disasters in the Chure region in Nepal, a region with high importance in terms of ecological values and restoration needs. Both floods and landslides are often complimentary and require comprehensive assessments at household level for better understanding of people's underlying vulnerabilities and resilience towards these hazards.

The main objective of this study is to examine whether ecosystem restoration reduces vulnerabilities to hazards by providing ecosystem services. Here, we (1) assessed the effectiveness of restoration project that aims to reduce natural hazards; (2) examined whether the concept of Eco-DRR or NbS is integrated into such restoration projects; (3) assessed people's perceptions towards the availability of ecosystem services in both pre-and post-restoration periods; and (4) provided some recommendations for further integrating ecosystem-based interventions in Chure region of Nepal. We used a multi-pronged approach in collecting data, which included site inspection for assessing the integration of Eco-DRR or NbS criteria in restoration projects, a questionnaire survey for understanding people's experience towards hazards and ecosystem services and remote sensing for analyzing land use and land cover change in the area. These data were used to assess community vulnerabilities to water-induced disasters considering benefits provided by ecosystem restoration. Such research is crucial for both managers and policy-makers to develop plans for effective disaster risk reduction [35].

2. Materials and methods

2.1. Study area

The study area covers an area of 30 km² encompassing a part of the Jaladh river and adjoining area (26°57'50.24" – 26°52'59.53"N, 85°59'29.92" – 86°00'47.27"E) of Dhanusa district, Nepal. The area is a representative sample of the Chure, one of the five physiographic regions of Nepal that cover 13.6% of the country's area [36]. The Jalad river is mainly fed by Chure hills and therefore has a high seasonal water fluctuation. The river originates from the Mahabharat range, passes through the east-west highway and meanders to the south [37]. The river consists of three tributaries: *Jalad Khola*, *Hachuwa Khola* and *Bhaluwa Khola*. We carried out field visits in and around four villages— Madhubasha, Chaukitol, Pushpalpur and Digampur — situated in the middle of the Jalad river basin (Fig. 1).

2.2. Data collection

2.2.1. Questionnaire survey

We conducted a questionnaire survey with 92 respondents in 2021, drawn using a systematic random sampling procedure, from households in four villages: Madhubasha, Chaukitol, Pushpalpur, and Digampur. During the survey, we randomly selected a house and thereafter every alternate house, based on the household pattern of the village, covering 65% of households. First, we asked peo-

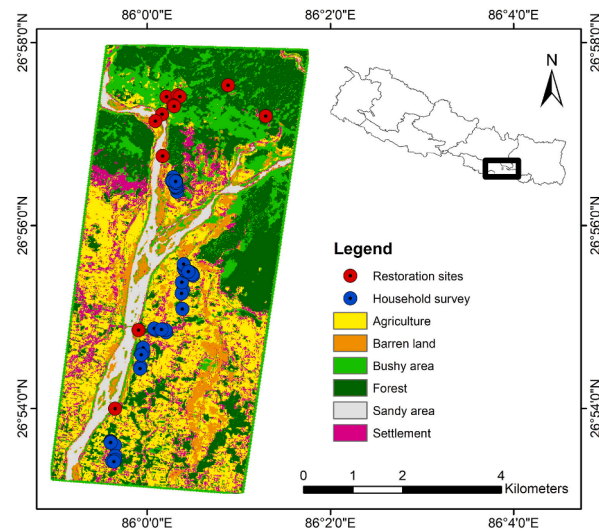


Fig. 1. A land-use and land cover map of the Jalad river basin, Dhanusha, Nepal with the location of household survey and restoration project sites.

ple on sight if he/she was a local inhabitant and if the house belonged to him/her. After confirming respondents' local connections (e.g., regular resident) informally, we talked for a while giving our introduction, including forest, water and disasters that matters to everyone's life. It played a crucial role to establish a connection with respondents [38]. We then recorded respondents' opinions on the occurrence of hazards on a dichotomous scale (e.g., yes, no) and towards the statements related to the availability of ecological services during pre and post-project intervention on a three-point scale: yes, partially and no [39] (See Appendix A: Tables 1 and 2). These data were used as proxy indicators of sensitivity in vulnerability analyses (see Section 2.3 and Table 1 for details). The age of the respondent ranged from 20 years to 81 years with a mean of 48 ± 14.67 years. These respondents represented a large variability in terms of occupation (agriculture-59%, business –21%, job –14%, laborer-15%). Of the 92 respondents, 76% had livestock, which

Table 1
Indicators and their definition used in the vulnerability assessment.

Vulnerability Indicators	Description of indicators	Data source and weight of indicators ^a
Exposure	Distance from the Jalad River: It includes the Euclidian distance between the respondent's house and the Jalad River. The more distance from the river, the low exposure will be towards the hazard [40]. Since the terrain is flat in the village, there is no differential influence of the elevation.	Geographical Information System (Distance to the river in m)
Sensitivity	1. Availability of water: The less availability of water resources and the more competition to use limited resources [41]. It is a cumulative score of water demand, functionality and availability based on the respondent's opinion on a scale (yes, partially and no) on the following statements: <ul style="list-style-type: none"> - Water availability in wells and tube wells is abundant (past and present) - There are functional water springs during dry seasons (past and present) 	Questionnaire survey (section 2.2.1) (Yes – 2, partially 1, no- 0)
	2. Availability of forest resources: Less availability of forest resources results in more competition to use limited resource [42]. It is a cumulative score based on the respondent's opinion on a Likert scale on the following statements: <ul style="list-style-type: none"> - There are abundant NTFP (e.g., mushrooms, fruit, rattans) (past and present) - You have to travel more now to get access to fodder (past and present) - Access to firewood is easier (past and present) 	Questionnaire survey (section 2.2.1) (Yes – 2, partially 1, no- 0 or vice versa based on positive and negative statement)
	3. The abundance of selected wildlife: The abundance of species is an indicator of the quality of the ecosystem and supports a range of human needs [43]. It is a cumulative score based on the respondent's opinion on a Likert scale on the following statements: <ul style="list-style-type: none"> - There are fewer bees and butterflies (past and present) - More wild birds can be seen (past and present) 	(Yes – 2, partially 1, no- 0 or vice versa based on positive and negative statement)
	4. Major occupation (farming or not). It is based on a household survey about the major occupation of the household as (a) farming, (b) farming and others (c) other (non-farming). The higher the ecosystem degradation, the more vulnerability of farmers will be due to limited forage and fodder [44].	Questionnaire survey (section 2.2.1) (Farming 0, Farming and other 1, non-farming 2)
Adaptive Capacity	1. Effectiveness of restoration projects: The high number of effective restoration projects renders more benefits to nearby households [42]. It is calculated as the number of effective restoration projects within a 2.5 km radius of a household.	Field observation (section 2.2.3) (Number of restoration sites)
	2. The ratio of forest to non-forest: The higher the forest area, the higher the adaptive capacity because of less human intervention in natural forest conditions [45]. It is calculated as a ratio of forest to non-forest within a 2.5 km radius of a household.	Remote sensing (section 2.2.2) (Proportion of forest to the non-forest area)

^a The weightage of indicators is provided in the parenthesis.

is reared by installed feeding (39.13%) and grazing in the forest (8.7%). Forest is the major source of energy for 27.17% and 63.04% of the household for cooking and heating respectively. The majority of people (48.91%) rely on community tube-well for drinking water (Appendix A. Table 2).

2.2.2. Remote sensing

We used Sentinel-2A and Sentinel-2B satellite images of March 13, 2016, and March 02, 2020, for the land use and land cover classification, which are available at the US Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (<http://glovis.usgs.gov/>). Cloud and shadow-free images with minimum seasonal variation were selected to improve the accuracy of image classification.

The study area has predetermined five land use and land cover (LULC) categories, similar to national-level LULC [46]: agriculture, barren, forest, sand and settlement. For each of the predetermined classes, we used the time-lapse function in Google earth images in Google Earth Pro and drew 64 polygons, covering representative samples for image classification for 2016. Google consists of high resolutions satellite images and is easier for visual interpretation of land cover type with relatively little effort. We recorded LULC data for training and validation for 2020 from the field using a handheld GPS device (Garmin eTrex). We used ERDAS imagine 2015 software for layer stacking (converting the bands into a single layer), image processing and supervised classification of the satellite imageries [47] using the maximum likelihood algorithm [48]. Layer stacking included images with band B11 (SWIR), B8 (Near-infrared), B4 (Red) B3 (Green) and B2 (Blue) [49]. Before image classification, we projected satellite images to Universal Transverse Mercator (UTM) zone 45 N, and carried out noise and haze [50], including atmospheric corrections [51]. The overall accuracies (OA) of image classification were 80% and 83% for the years 2016 and 2021 respectively [52]. The LULC map was converted into a binary (forest vs non-forest map) by merging agriculture, barren, sand and settlement as non-forest and computed the proportion of forest to non-forest within a 1.25-km radius (average distance between every two houses in three villages) of every household for both 2016 and 2021. These data were used as a proxy indicator of adaptive capacity for vulnerability analysis (see section 2.3 and Table 1 for details).

2.2.3. Field observation

We visited project restoration sites after consultation with the local community. Here, a restoration site is a location where activities designed for regulating hazards (e. g., embankments, plantation etc.) are implemented. We carefully observed how nature-based solutions are implemented using a simple checklist (Table 2) by reviewing the relevant literature related to both Eco-DRR and Nbs [24,31,33,34]. At the same time, we assessed if a restoration project was successful based on two conditions. The first criterion was a reduction in soil erosion and river bank cutting, which is determined visually. Secondly, we looked at the physical status of the restoration infrastructure. If a restoration infrastructure was undamaged and was in working condition, we considered it to meet the second criterion. Thus, a successful restoration site needed to have both (a) control of soil erosion and/or river bank cutting and (b) undamaged working conditions. We computed the total number of successful restoration projects within 1.25 km of a house as a proxy indicator of adaptive capacity in vulnerability analysis at household level (see section 2.3 and Table 1 for details).

2.3. Data analysis: vulnerability assessment

Vulnerability is multidimensional and is determined by the interrelationship of socioeconomic, environmental, institutional, and technological factors [53,54]. Therefore, an index to measure vulnerability is helpful to make comparisons among different communities or systems. First, indicators are selected, then weights are assigned to these indicators and finally aggregated to form an index. Indicators and indices are useful in representing a complex reality in simpler terms. There are two approaches in the selection of indicators, data-driven and theory-driven [55]. The selection of indicators here is based on theories and the availability of data related to the nature and causes of vulnerability of the community to disasters (Table 1). Although these indicators may not provide an exhaustive list but are certainly important while assessing household vulnerability to disasters.

Altogether seven vulnerability indicators— exposure (1), sensitivity (4) and adaptive capacity (2) were taken to determine the vulnerability of each household in the study area. The indicator for exposure includes the proximity to the hazard-prone area. Sensitivity includes the availability of resources (water, forest, and animal) and occupation (farming or non-farming). A community's adaptive capacity is measured based on the effectiveness of existing restoration projects and land cover/land use in and around their households. The response we obtained from the questionnaire survey (yes, partially and no) were transformed to a number interval scale of 0, 1 and 2 depending on scales of positive (e.g., "water availability in wells and tube-wells are abundant") or negative (e.g., "there are fewer bees and butterflies") statements [56]. The scores given to each contributing factor were summed [57] and divided by the total maximum possible score to generate a unique indicator value under each theme of ecosystem restoration (e.g., water, forest, wildlife). However, the score for the effectiveness of the restoration project was determined as the number of effective restoration projects within a 2.5 km radius of a household.

The vulnerability measurement can be conducted in various ways and methods, depending on the fields of specialization. The vulnerability index is a quantitative assessment of a system's vulnerability and is usually computed by aggregating the selected set of vulnerability indicators. Several researchers have outlined vulnerability as a function of exposure, sensitivity, and adaptive capacity [58–61]. In general, vulnerability is positively related to a household's exposure and sensitivity to disasters, but negatively related to a household's adaptive capacity to cope with the negative effects [62]. Here we used a framework by Intergovernmental Panel on Climate Change (IPCC) to assess vulnerability [63].

For evaluating the impacts of hazards, vulnerability is often measured by constructing an index of vulnerability in case of any natural hazards [64]. This method can be used to measure the vulnerability to any natural hazards. However, the types of natural haz-

ards are often determined before designing questionnaire surveys targeting particular natural hazards [65]. In this study, the survey was designed to study the change in natural hazards due to restoration activities. Hence, the vulnerability index is measured here as a function of exposure, sensitivity, and adaptive capacity, conditional upon the flood and landslide events concerning restoration activities.

According to the framework proposed by Fussler and Klein (2006) [66], exposure (E) and sensitivity (S) together compose the potential impact (PI), while adaptive capacity (AC) is the potential of a system to cope with these impacts.

$$PI = E \times S \quad (1)$$

People who live in exposed areas are likely to become a 'potentially vulnerable group'. This potentially vulnerable group can be divided into two - with and without adaptive capacity [67]. Vulnerability therefore can be expressed as the following equation:

$$V = PI - PI \times AC \quad (2)$$

or,

$$V = PI (1 - AC) \quad (3)$$

2.3.1. Normalizing indicators

The term 'normalization' refers to the transformation of indicator values measured on different scales and in different units into unitless values on a common scale. These different units cannot be aggregated without normalization. They are normalized using a minimum-maximum transformation approach [68] to fit them between 0 and 1 scale. Here, we define '0' as 'lowest' and '1' as 'highest'.

Each indicator under three main components (E, S and A) were calculated for each household using the past and present scenarios (i.e., before and after restoration). As different indicators are calculated at different scales, the normalization of the indicators is applied depending upon whether the indicator is positively or negatively correlated as follows. The following formula (Equations 2 and 3) was used.

If the increase in indicator values increases vulnerability:

$$X_{ij} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}} \quad (4)$$

If the increase in indicator values decreases vulnerability:

$$X_{ij} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}} \quad (5)$$

Where, where X_{ij} , X_{\max} , and X_{\min} are the original values of the j th indicator for the i th unit and maximum and minimum values of all the units considered, respectively.

The lack of a coping component for a positive contribution to vulnerability is standardized as reverse values having a negative relationship with vulnerability.

2.3.2. Determining weightage of indicators

The indicators that receive a greater (or lesser) weight thus have a greater (or lesser) influence on the respective vulnerability component and on overall vulnerability. The different weights assigned to indicators can be derived from various methods such as existing literature, stakeholder information or expert opinion or statistical variance method. Here, differential weights are calculated by the following statistics-based weight (e.g., variance-based weight) by Iyengar and Sudarshan [69]. The variance-based method calculates weights using Equation (7), where weights are assumed to vary inversely with standard deviations to ensure that large variation in any one of the indicators would not unduly dominate the contribution of the rest of the indicators and distort interunit comparisons.

$$VI = \sum_{j=1}^n (w_j \times x_{ij}) \quad (6)$$

$$w_j = \frac{1}{\left(SD_i \times \sum_{j=1}^n \left(\frac{1}{SD_i} \right) \right)} \quad (7)$$

Where, w_j is the weight of the j th indicator and x_{ij} is the normalized value of X_{ij} and SD is the standard deviation.

2.3.3. Aggregation of indicators

Once the different indicators of a vulnerability component have been evaluated and weighted, they were aggregated into three vulnerability components exposure, sensitivity and adaptive capacity. For aggregating individual indicators into composite indica-

tors, here a method called ‘weighted arithmetic aggregation’ was applied. Individual indicators are multiplied by their weights, summed and subsequently divided by the sum of their weights to calculate the composite indicator of a vulnerability component.

Statistical comparisons were performed using Wilcoxon signed-rank test for pre and post vulnerability indices and a proportion test (test statistic Z) for type of responses towards ecosystem restoration.

3. Results

3.1. Disaster and restoration

Almost all respondents (94%) experienced disasters (e.g., flood, sedimentation and soil erosion). Our results showed no significant difference between the proportion of respondents who believed that floods, sedimentation and soil erosion are common in past (68%) compared to those who had a similar perception now (75%). However, a significantly high proportion of respondents agreed with the statement “More incidences of flashflood have been observed” now (85%) as compared to those who had a similar perception (58%) ($\chi^2 = 15.625$, $P < 0.001$). Regarding the perception of ecological services, 46% of respondents noted that water availability in wells and tube wells was abundant now, which was not significantly different from a proportion of respondents who believed the same in past (50%). Significantly fewer people (69%) compared to those in past (83%) believed that “there are functional water springs during dry seasons” ($\chi^2 = 16.46$, $P < 0.0001$). However, a significantly low proportion of people believe that they “have to travel more to get drinking water” now compared to the past ($\chi^2 = 58.79$, $P < 0.0001$). Interestingly, people reporting frequent encounters with wild animals were significantly high now (89%) than those who believed in past (39%) ($\chi^2 = 47.843$, $P < 0.0001$), so was among people who believed “abundant availability of NTFP” now (59%) compared to those in past (34%) ($\chi^2 = 10.58$, $P = 0.001$). A total of 59% of respondents observed “easier access to firewood” now, which was not significantly different to those who observed the same (54%).

A total of 13 restoration project sites were observed during the field visit (Fig. 2). These restoration projects were of the following three categories: (a) check-dam along river gullies (n = 9), (b) river embankment (n = 3), (c) afforestation (n = 1). Check-dam along river gullies is the most common restoration project, mainly constructed upstream of the river. It accumulates a rapid flow of water as soon as it receives rain. The dams included deeply wired gabion check dams (1–2 m) along the river path, including a wired embankment (3–6 m) on either side along the riverbank. Such dams were successful in preventing gully erosion, resulting conversion of a “V” shaped riverbed into a “U” shaped riverbed. River embankments were of various types, namely (a) saw-toothed gabion spur dikes, (b) concrete dams and (c) gabion retaining embankments. The saw-toothed gabion spur dikes included a series of the saw (9 m



Fig. 2. Representative restoration sites of the Jalad River Basin. A: check dam in river gullies (site 2), B: river embankment (site 12), C: afforestation (site 10), and D: erosion breaker (site 13).

in length, 1.5 m in height and 3 m in width), placed 30–40 m apart. The afforestation included a eucalyptus plantation in a 35-ha of land along the riverside to protect it from being washed away during floods (see Fig. 2).

We evaluated 62% (8 out of 13) restoration project sites as being successful as per our criteria (Table 2). However, the application of ecosystem-based adaption criteria in the restoration project site suggested that none of the restoration projects met our criteria 3, 5 and 6 (Table 2). The restoration project sites (1 and 2) were the most integrated ones with ecosystem-based adaptation (scored 46% of ideal weightage, ideal average weightage = 24), whereas site 4 received no score at all (Table 2).

3.2. Land use and land cover change

The spatial distribution of major LULC classes in the study area for 2016 and 2021 is shown in Fig. 3. There was a reduction in forest area, and an increase in agricultural land and settlement during the investigated years whereas the changes in the barren area and bushy were negligible (Tables 3 and 4). An improvement in bushy and grassland along the riverbank and northern part of the study

Table 2

Application of ecosystem-based adaptation criteria in the restoration project site. Sites with an asterisk (*) suggest effective restoration based on our criteria.

SN	Criteria	Site 1*	Site 2*	Site 3*	Site 4	Site 5*	Site 6*	Site 7*	Site 8	Site 9	Site 10	Site 11	Site 12*	Site 13*
1	The use of local resources and materials is done.	+++	+++	++	-	+++	+++	+++	+++	++	-	++	+++	++
2	Community participation is ensured in project planning, implementation and monitoring.	++	++	++	-	++	++	+	+	+	+	+	+	+
3	The needs of local people especially right-based groups are ensured and prioritized.	-	-	-	-	-	-	-	-	-	-	-	-	-
4	The management of forest ecosystems is carried out considering the surrounding landscape (landscape approach).	++	++	++	-	+	+	+	-	+	+	-	-	-
5	The guidelines for forest restoration with a focus on soil and water conservation is followed.	-	-	-	-	-	-	-	-	-	-	-	-	-
6	There is a well-defined land use policies and guidelines to restrict future development.	-	-	-	-	-	-	-	-	-	-	-	-	-
7	The use of intervention is justified in terms of alternatives and the scale of intervention.	++	++	++	-	+	+	+	+	+	-	-	+	+
8	The integration of local knowledge has been taken care of in the restoration project.	++	++	++	-	++	++	+	+	+	-	-	-	-
Weightage average		11	11	10	0	9	9	7	6	6	2	3	5	4

Note: The more plus (+) signs the more applicable is each criterion. Weightage is given in parentheses: +++ highly integrated (3), ++ moderately integrated (2), + to some extent integrated (1), - not integrated (0).

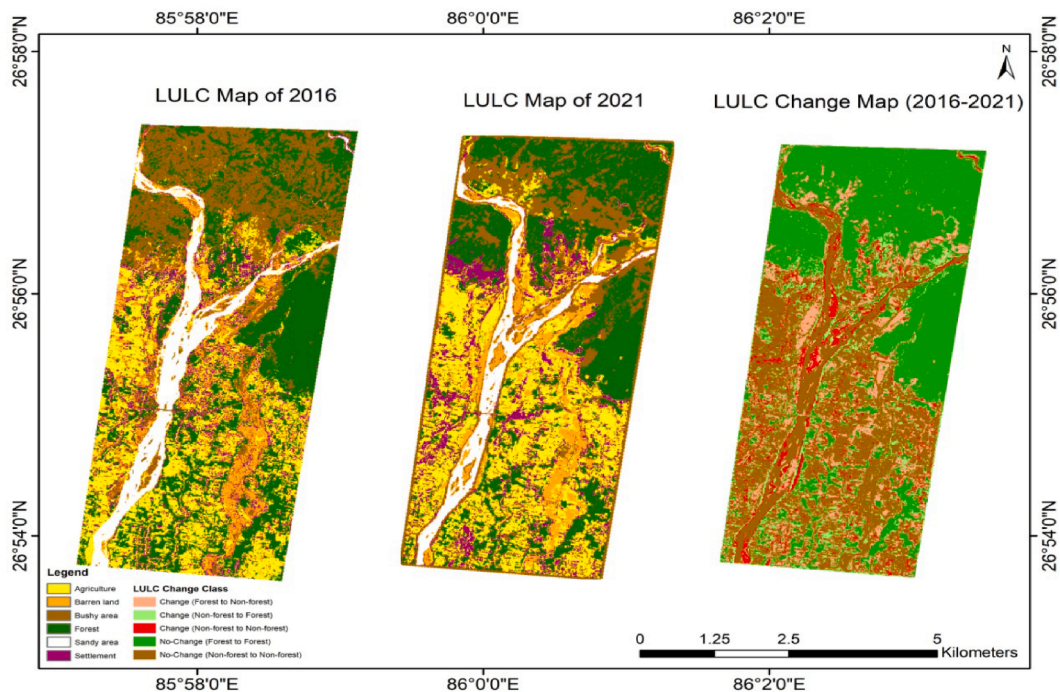


Fig. 3. Pattern of land use and land cover of the Jalad river in the years 2016 and 2021.

Table 3
The pattern of land use and land cover of the Jalad river basin for 2016 and 2021.

SN	LULC	2016		2021	
		Area (ha)	Area (%)	Area (ha)	Area (%)
1	Agriculture	667.88	22.90	795.46	27.27
2	Barren land	231.00	7.92	235.26	8.07
3	Bushy area	525.21	18.01	540.46	18.53
4	Forest	967.13	33.16	845.06	28.97
5	Sand	231.88	7.95	163.25	5.60
6	Settlement	293.59	10.07	337.23	11.56

Table 4
A comparison matrix of forest cover change between 2016 and 2021.

SN	LULC change class	Area (ha)
1	Change (forest to non-forest)	372.96
2	Change (non-forest to forest)	257.63
3	Change (non-forest to non-forest)	221.67
4	No change (forest to forest)	1254.12
5	No change (non-forest to non-forest)	1070.57
	Total	3176.95

area suggested an influence of the restoration project. Similarly, the results show that forest area decreased from 2016 to 2021 at a rate of 2.52% per year.

3.3. Restoration and vulnerabilities

The weightage of indicators used to assess the vulnerability of households to disasters suggested that the “distance to the river” was the most important indicator in past, which now shifted towards water demand. Occupation seems to get the least weightage both in the past and after restoration project intervention. The vulnerability index after restoration suggests a reduction of vulnerability in 88% of households. The average vulnerability index of households reduced from 0.044 in the past to 0.017 now. As expected, we found a significant decrease in vulnerability in the post-project duration (Wilcoxon signed-rank test, $p < 0.001$, Fig. 4).

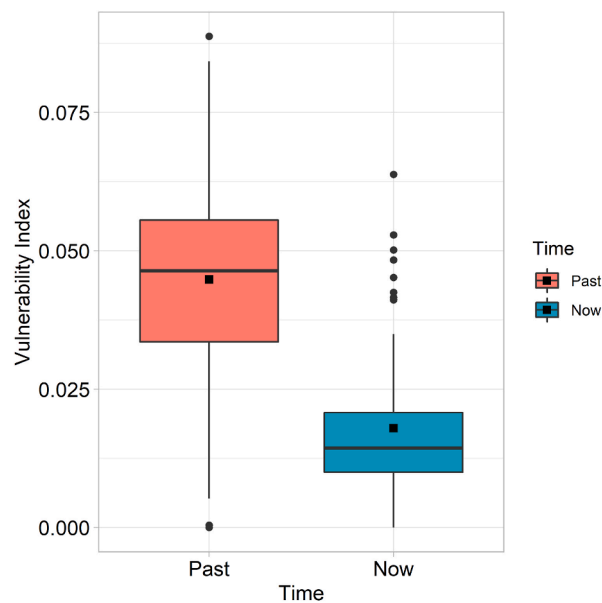


Fig. 4. Box plot showing the vulnerability index of 92 households in the past (before the restoration project) and now. In each box plot, the central mark indicates the median, the dot mark indicates the mean, the bottom and top edges of the box indicate the interquartile range (IQR), and the whiskers represent the maximum and minimum data points.

4. Discussion & conclusion

We provide empirical evidence that restoration projects, despite being small and localized in nature, have ecological benefits and help in reducing vulnerabilities to disaster. Our results show that a restoration project well-aligned with ecosystem-based adaptation at landscape approach would have direct benefits in both mitigating disaster risks and restoring degraded ecosystem services in the long run. This aligns with several studies that have shown that ecosystems render critical services in regulating and attenuating various types of hazards [19,70,70–72]. Sudmeier-Rieux et al. (2021) reviewed links and cost-effectiveness of ecosystems in reducing specific hazards based on published research articles and noted strong links in several cases, particularly, the stabilization of steep slopes by the vegetation [73].

Flood is the most common and serious disaster, and mitigation projects spanned from check dams to afforestation in the potential areas. The current restoration projects are ad hoc, small scale and focused on reducing water flow and sediment accumulation upstream of the river basin. Such relatively small and localized restoration projects are relatively inadequate in rendering ecosystem services, as suggested by our respondents. Except for “there is a frequent encounter with wild animals”, respondents made similar judgments on the availability of ecosystem services in past and now. Restoration of ecosystem services such as the revival of water springs and availability of non-timber forest products is possible when restoration projects are at the landscape or basin level. Several studies provide evidence that land-use change alters natural habitats and the ecosystem services that they provide [74–78]. In our study area, there was a net loss of forest area due to conversion into agricultural lands and human settlements, while marginal gains in the bushy area around project intervention sites, suggesting a localized restoration approach.

The structure and composition of landscapes influence biodiversity and ecosystem processes not only in isolation but in combination with other factors such as climate change [79,80]. A forest landscape provides multiple services such as carbon sequestration, soil nutrient cycling, flood protection, supply of food and timber etc. Studies show that ecosystem services interact among themselves, and synergies arise when multiple services are enhanced simultaneously [81,82]. A natural and well-managed forest typically has higher productivity and biomass, higher biodiversity, and better provisioning of ecosystem services [83,84], which greatly contribute to securing resilient communities. The forest landscape in the Jalad river basin is under the management of local community, which is decentralized forest management promoted to enhance sustainable forest use and reduce rural poverty. There are some concerns that community forests may not serve biodiversity conservation—although positive results are also reported—due to a lack of explicit conservation objectives and an increasingly high focus towards the commercial gains of such forests. We noticed that small-scale and inexpensive projects made a substantial contribution to reducing erosion and flash floods, and better integration will maximize the benefits.

We call for a complete shift in existing small-scale and site-specific restoration intervention with the ecosystem-based approach. This approach focuses on the integration of ecological principles in designing and developing projects, including the use of local knowledge and resources and the involvement of local communities in both decision-making and implementation projects [85]. This is important on several fronts. Disasters in Chure region of Nepal are mostly of anthropogenic origin, although natural hazards are common and exacerbated by stresses induced by humans [86]. Here, the disaster mitigation approach includes the construction of a gabion embankment downstream near human settlements. While such an approach is justifiable to reduce impeding risk to the community, it is more important to focus on Chure which quickly accumulates rainwater and washes away soil, causing massive floods and sedimentation downstream [87]. The Chure landscape has high human-induced stresses such as forest encroachment, forest fire, urbanization, infrastructure development and illegal harvesting [88–90]. Consequently, a dire shortage of key ecosystem services such as freshwater provision has been reported, including a surge in the intensity and frequency of hazards [91,92].

One might argue that improving resilience can be achieved through reducing exposure aided by the construction of dams and embankment. However, resilience depends on various social, biophysical and economic dimensions—specific to site and time—that have a non-linear and complex relationship. The quality of ecosystem services (e.g., water and forest availability etc.) renders a significant improvement in the sensitivity and adaptive capacity and thus reduces vulnerability. Given highly fragile geology and sensitivity to environmental disturbance, both policymakers and disaster risk reduction professionals need to acknowledge and incorporate an ecosystem-based approach including local knowledge and/or indigenous knowledge and community perspectives in future restoration projects. Our approach to DRR integrates social and biophysical interactions and provides an outline for future studies and a pathway to realign Chure conservation in Nepal.

5. Study limitation

We are aware of possible caveats induced while selecting the sample (e.g., selection of interviewees) and indicators. Since we collected data at household level and covered more than 75% households in the study area, the sample adequacy is not questioned in our study. There is of course a question of selection bias of interviewees. We collected household-level (family-level) information (e.g., occupation), ensuring that there would be little variations within a family. Survey questions on the availability of ecosystem services before and after restoration projects were asked in an informal setting, allowing respondents to relate and think about questions in focus. This, however, could induce limited bias due to individual perception. Despite these drawbacks, we think the results are reasonably robust as we integrated data from remote sensing and field observation, which are used to calculate vulnerabilities at household level. More attention should also be given to empirical studies per se collecting data on ecosystem services to explore pathways of regulating ecosystem services to disaster risk reduction.

Credit author statement

Prakash K Paudel: Conceptualization, Methodology, Data collection, Data analysis, Writing – review & editing, Supervision, Funding acquisition. Arjun Lamichhane: Data collection, Data analysis, Writing – original draft. Rabin Bastola: Methodology, Data Analysis, Writing – review & editing. Krishna Prasad Acharya: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

PKP and AL acknowledge funding support from Asia Pacific Network for Global Climate Change under grant number (CRRP2021-04MY-Paudel).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijdr.2023.103647>.

References

- [1] T. Bannister, Mapping Geohazards in the Churia Region of Nepal: an Application of Remote Sensing and Geographic Information Systems, 2016. <http://adsabs.harvard.edu/abs/2016MsT.....51B>. (Accessed 1 June 2021). accessed.
- [2] P.K. Paudel, B.P. Bhattarai, P. Kindlmann, An overview of the biodiversity in Nepal, in: P. Kindlmann (Ed.), *Himal. Biodivers. Chang. World*, Springer Netherlands, 2012, pp. 1–40. http://link.springer.com/chapter/10.1007/978-94-007-1802-9_1. (Accessed 10 November 2014). accessed.
- [3] B.P. Bhandari, S. Dhakal, A multidisciplinary approach of landslide characterization: a case of the Siwalik zone of Nepal Himalaya, *J. Asian Earth Sci.* X. 5 (2021) 100061, <https://doi.org/10.1016/j.jaesx.2021.100061>.
- [4] H. Gurung, N. Khanal, Landscape processes in Chure range central Nepal, *Nepal J.* 17 (1986).
- [5] K.P. Pokhrel, Chure forestry conservation and management plan: a case study of Arghakhanchi district, Nepal, *J. Geogr. Reg. Plann.* 6 (2013) 172–183, <https://doi.org/10.5897/JGRP12.088>.
- [6] M. Ghimire, Historical land covers change in the chure-Tarai landscape in the last six decades: drivers and environmental consequences, in: A. Li, W. Deng, W. Zhao (Eds.), *Land Cover Change its Eco-Environ. Responses Nepal*, Springer, Singapore, 2017, pp. 109–147, https://doi.org/10.1007/978-981-10-2890-8_5.
- [7] D. Bishwokarma, S.J. Thing, N.S. Paudel, Political ecology of the chure region in Nepal, *J. For. Livelihood.* 14 (2016) 84–96, <https://doi.org/10.3126/jfl.v14i1.23164>.
- [8] M. Ghimire, Historical land covers change in the chure-Tarai landscape in the last six decades: drivers and environmental consequences, in: A. Li, W. Deng, W. Zhao (Eds.), *Land Cover Change its Eco-Environ. Responses Nepal*, Springer, Singapore, 2017, pp. 109–147, https://doi.org/10.1007/978-981-10-2890-8_5.
- [9] DFRS, *State of Nepal's forests, Forest Resource Assessment (FRA) Nepal*, Department of Forest Research and Survey (DFRS), Kathmandu, Nepal, 2015.
- [10] R.P. Acharya, T.N. Maraseni, G. Cockfield, Local users and other stakeholders' perceptions of the identification and prioritization of ecosystem services in fragile mountains: a case study of chure region of Nepal, *Forests* 10 (2019) 421, <https://doi.org/10.3390/f10050421>.
- [11] P. Bhandari, M. Kc, S. Shrestha, A. Aryal, U.B. Shrestha, Assessments of ecosystem service indicators and stakeholder's willingness to pay for selected ecosystem services in the Chure region of Nepal, *Appl. Geogr.* 69 (2016) 25–34, <https://doi.org/10.1016/j.apgeog.2016.02.003>.
- [12] D. Khadka, A. Aryal, K.P. Bhatta, B.P. Dhakal, H. Baral, Agroforestry systems and their contribution to supplying forest products to communities in the chure range, Central Nepal, *Forests* 12 (2021) 358, <https://doi.org/10.3390/f12030358>.
- [13] PCTMCDB, 2014. <https://chureboard.gov.np/?p=90>.
- [14] S. Dhyani, S. Lahoti, S. Khare, P. Pujari, P. Verma, Ecosystem based disaster risk reduction approaches (EbDRR) as a prerequisite for inclusive urban transformation of Nagpur city, India, *Int. J. Disaster Risk Reduc.* 32 (2018) 95–105, <https://doi.org/10.1016/j.ijdr.2018.01.018>.
- [15] M.A. Palmer, J. Liu, J.H. Matthews, M. Mumba, P. D'Odorico, Manage water in a green way, *Science* 349 (2015) 584–585, <https://doi.org/10.1126/science.aac7778>.
- [16] A. Pagano, I. Pluchinotta, P. Pengal, B. Cokan, R. Giordano, Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: a participatory System Dynamics Model for benefits and co-benefits evaluation, *Sci. Total Environ.* 690 (2019) 543–555, <https://doi.org/10.1016/j.scitotenv.2019.07.059>.
- [17] W. Chen, W. Wang, G. Huang, Z. Wang, C. Lai, Z. Yang, The capacity of grey infrastructure in urban flood management: a comprehensive analysis of grey infrastructure and the green-grey approach, *Int. J. Disaster Risk Reduc.* 54 (2021) 102045, <https://doi.org/10.1016/j.ijdr.2021.102045>.
- [18] P. Sukhdev, "Potsdam Initiative-Biological Diversity 2010". *The Economic Significance of the Global Loss of Biological Diversity*, 2008 TEEB Interim Report CBD COP-9.
- [19] M. Estrella, N. Saalimaa, Ecosystem-based Disaster Risk Reduction (Eco-DRR): an Overview, *Role Ecosyst. Disaster Risk Reduct.* 332 (2013) U. N. Univ. Press Tokyo.
- [20] A. Onuma, T. Tsuge, Comparing green infrastructure as ecosystem-based disaster risk reduction with gray infrastructure in terms of costs and benefits under uncertainty: a theoretical approach, *Int. J. Disaster Risk Reduc.* 32 (2018) 22–28.
- [21] D.A. Heemsbergen, M.P. Berg, M. Loreau, J.R. Van Hal, J.H. Faber, H.A. Verhoef, Biodiversity effects on soil processes explained by interspecific functional dissimilarity, *Science* 306 (2004) 1019–1020.
- [22] O.L. Petchey, A. Hector, K.J. Gaston, How do different measures of functional diversity perform? *Ecology* 85 (2004) 847–857.
- [23] Doswald & Estrella, Promoting Ecosystems for Disaster Risk Reduction and Climate Change Adaptation: Opportunities for Integration, 2015. <https://muchanut.haifa.ac.il/index.php/he/component/k2/item/280-doswald-estrella-2015-promoting-ecosystems-for-disaster-risk-reduction-and-climate-change-adaptation-opportunities-for-integration>.
- [24] A. Andrade, E. Cohen-Shacham, J. Dalton, S. Edwards, D. Hessenberger, S. Maginnis, S. Maynard, P. McElwee, R. Murti, C. Nelson, *IUCN Global Standard for Nature-Based Solutions: a User-Friendly Framework for the Verification, Design and Scaling up of NBS*, IUCN Gland Switz., 2020.
- [25] R. Munang, I. Thiaw, K. Alverson, J. Liu, Z. Han, The role of ecosystem services in climate change adaptation and disaster risk reduction, *Curr. Opin. Environ. Sustain.* 5 (2013) 47–52, <https://doi.org/10.1016/j.cosust.2013.02.002>.
- [26] V. Lo, Synthesis Report on Experiences with Ecosystem-Based Approaches to Climate Change Adaptation and Disaster Risk Reduction, 2016, <https://doi.org/10.13140/RG.2.2.20597.47840>.

- [27] C.T. Nguyen, B. Van Nguyen, Application of flood vulnerability index in flood vulnerability assessment: a case study in Mai Hoa commune, Tuyen Hoa district, Quang Binh province, Sustain. Water Resour. Manag. 5 (2019) 1917–1927, <https://doi.org/10.1007/s40899-019-00337-y>.
- [28] S. Pathak, H.K. Panta, T. Bhandari, K.P. Paudel, Flood vulnerability and its influencing factors, Nat. Hazards 104 (2020) 2175–2196, <https://doi.org/10.1007/s11069-020-04267-3>.
- [29] R. Costache, S.A. Ali, F. Parvin, Q.B. Pham, A. Arabameri, H. Nguyen, A. Crăciun, D.T. Anh, Detection of areas prone to flood-induced landslides risk using certainty factor and its hybridization with FAHP, XGBoost and deep learning neural network, Geocarto Int. (2021) 1–36.
- [30] T. Page, N.A. Chappell, K.J. Beven, B. Hankin, A. Kretzschmar, Assessing the significance of wet-canopy evaporation from forests during extreme rainfall events for flood mitigation in mountainous regions of the United Kingdom, Hydrol. Process. 34 (2020) 4740–4754.
- [31] S. Kato, W. Huang, Land use management recommendations for reducing the risk of downstream flooding based on a land use change analysis and the concept of ecosystem-based disaster risk reduction, J. Environ. Manag. 287 (2021) 112341.
- [32] C.S. Ferreira, S. Mourato, M. Kasanin-Grubin, A.J. Ferreira, G. Destouni, Z. Kalantari, Effectiveness of nature-based solutions in mitigating flood hazard in a Mediterranean peri-urban catchment, Water 12 (2020) 2893.
- [33] I.U. for C. of Nature (IUCN), Guidance for Using the IUCN Global Standard for Nature-Based Solutions, 2020.
- [34] UNDRR, Ecosystem-Based Disaster Risk Reduction: Implementing Nature-Based Solutions for Resilience, United Nations Office for Disaster Risk Reduction – Regional Office for Asia and the Pacific, Bangkok, Thailand, 2020.
- [35] A.R. Hamidi, Z. Zeng, M.A. Khan, Household vulnerability to floods and cyclones in Khyber Pakhtunkhwa, Pakistan, Int. J. Disaster Risk Reduc. 46 (2020) 101496.
- [36] B.K. Singh, Land Tenure and conservation in chure, J. For. Livelihood. 15 (2017) 87–102, <https://doi.org/10.3126/jfl.v15i1.23092>.
- [37] R.K. Dahal, S. Hasegawa, N.P. Bhandary, P.P. Poudel, A. Nonomura, R. Yatabe, A replication of landslide hazard mapping at catchment scale, Geomatics, Nat. Hazards Risk 3 (2012) 161–192, <https://doi.org/10.1080/19475705.2011.629007>.
- [38] S. Adomah Bempah, A. Olav Øyhus, The role of social perception in disaster risk reduction: Beliefs, perception, and attitudes regarding flood disasters in communities along the Volta River, Ghana, Int. J. Disaster Risk Reduc. 23 (2017) 104–108, <https://doi.org/10.1016/j.ijdrr.2017.04.009>.
- [39] M.A. Patwary, W.T. O'Hare, M.H. Sarker, Assessment of occupational and environmental safety associated with medical waste disposal in developing countries: a qualitative approach, Saf. Sci. 49 (2011) 1200–1207, <https://doi.org/10.1016/j.ssci.2011.04.001>.
- [40] H.A. Zurqani, C.J. Post, E.A. Mikhailova, M.P. Cope, J.S. Allen, B.A. Lytle, Evaluating the integrity of forested riparian buffers over a large area using LiDAR data and Google Earth Engine, Sci. Rep. 10 (2020) 14096, <https://doi.org/10.1038/s41598-020-69743-z>.
- [41] V. Pandey, M. Babel, F. Kazama, A. Pandey, Analysis of a Nepalese water resources system: stress, adaptive capacity and vulnerability, Water Sci. Technol. Water Supply 9 (2009) 213–222, <https://doi.org/10.2166/ws.2009.245>.
- [42] G. Kröel-Dulay, J. Ransijn, I.K. Schmidt, C. Beier, P. De Angelis, G. de Dato, J.S. Dukes, B. Emmett, M. Estiarte, J. Garadnai, J. Kongstad, E. Kovács-Láng, K.S. Larsen, D. Liberati, R. Ogaya, T. Riis-Nielsen, A.R. Smith, A. Sowerby, A. Tietema, J. Penuelas, Increased sensitivity to climate change in disturbed ecosystems, Nat. Commun. 6 (2015) 6682, <https://doi.org/10.1038/ncomms7682>.
- [43] V. Peters, K. Campbell, G. Dienno, M. García, E. Leak, C. Loyke, M. Ogle, B. Steinly, T. Crist, Ants and plants as indicators of biodiversity, ecosystem services, and conservation value in constructed grasslands, Biodivers. Conserv. 25 (2016), <https://doi.org/10.1007/s10531-016-1120-z>.
- [44] M.M.G.T. De Silva, A. Kawasaki, Socioeconomic vulnerability to disaster risk: a case study of flood and drought impact in a rural Sri Lankan community, Ecol. Econ. 152 (2018) 131–140, <https://doi.org/10.1016/j.ecolecon.2018.05.010>.
- [45] M. Lindner, M. Maroschek, S. Netherer, A. Kremer, A. Barbat, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolström, M.J. Lexer, M. Marchetti, Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems, For. Ecol. Manag. 259 (2010) 698–709, <https://doi.org/10.1016/j.foreco.2009.09.023>.
- [46] IUCN, Land Cover of Nepal 2010, 2010. <https://rds.icimod.org/Home/DataDetail?metadatald=9224>.
- [47] E. Ayrey, S. Fraver, J.A. Kershaw, L.S. Kenefic, D. Hayes, A.R. Weiskittel, B.E. Roth, Layer stacking: a novel algorithm for individual forest tree segmentation from LiDAR point clouds, Can. J. Rem. Sens. 431 (2017) 16–27, <https://doi.org/10.1080/07038992.2017.1252907>.
- [48] A.W. Degife, F. Zabel, W. Mauser, Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data, Heliyon 4 (2018) e00919, <https://doi.org/10.1016/j.heliyon.2018.e00919>.
- [49] G.I.S. Geography, Sentinel 2 Bands and Combinations, 2021. <https://gisgeography.com/sentinel-2-bands-combinations/>.
- [50] A. Rahman, H.M. Abdulllah, M.T. Tanzir, M.J. Hossain, B.M. Khan, M.G. Miah, I. Islam, Performance of different machine learning algorithms on satellite image classification in rural and urban setup, Remote Sens. Appl. Soc. Environ. 20 (2020) 100410, <https://doi.org/10.1016/j.rsase.2020.100410>.
- [51] E. Castillo-López, J.A. Dominguez, R. Pereda, J.M. de Luis, R. Pérez, F. Piña, The importance of atmospheric correction for airborne hyperspectral remote sensing of shallow waters: application to depth estimation, Atmos. Meas. Tech. 10 (2017) 3919–3929, <https://doi.org/10.5194/amt-10-3919-2017>.
- [52] R.G. Congalton, A review of assessing the accuracy of classifications of remotely sensed data, Remote Sens. Environ. 37 (1991) 35–46, [https://doi.org/10.1016/0034-4257\(91\)90048-B](https://doi.org/10.1016/0034-4257(91)90048-B).
- [53] P. Blaikie, T. Cannon, I. Davies, B. Wisner, At Risk: Natural Hazards, People's Vulnerability, and Disasters, 1994.
- [54] B.H. Morrow, Identifying and mapping community vulnerability, Disasters 23 (1999) 1–18, <https://doi.org/10.1111/1467-7717.00102>.
- [55] K. Vincent, Creating an Index of Social Vulnerability to Climate Change in Africa, 2004.
- [56] M. Imran, K. Sumra, S.A. Mahmood, S.F. Sajjad, Mapping flood vulnerability from socioeconomic classes and GI data: linking socially resilient policies to geographically sustainable neighborhoods using PLS-SEM, Int. J. Disaster Risk Reduc. 41 (2019) 101288.
- [57] Y.T. Prasetyo, D.B. Senoro, J.D. German, R.A.C. Robielos, F.P. Ney, Confirmatory factor analysis of vulnerability to natural hazards: a household Vulnerability Assessment in Marinduque Island, Philippines, Int. J. Disaster Risk Reduc. 50 (2020) 101831.
- [58] T. Frazier, C. Thompson, R. Dezzani, A framework for the development of the SERV model: a Spatially Explicit Resilience-Vulnerability model, Appl. Geogr. 51 (2014) 158–172, <https://doi.org/10.1016/j.apgeog.2014.04.004>.
- [59] H.-M. Füssel, Vulnerability: a generally applicable conceptual framework for climate change research, Global Environ. Change 17 (2007) 155–167, <https://doi.org/10.1016/j.gloenvcha.2006.05.002>.
- [60] B.L. Turner, R.E. Kasperson, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, J.X. Kasperson, A. Luers, M.L. Martello, C. Polsky, A. Pulsipher, A. Schiller, A framework for vulnerability analysis in sustainability science, Proc. Natl. Acad. Sci. USA 100 (2003) 8074–8079, <https://doi.org/10.1073/pnas.1231335100>.
- [61] M.J. Metzger, M.D.A. Rounsevell, L. Acosta-Michlik, R. Leemans, D. Schröter, The vulnerability of ecosystem services to land use change, Agric. Ecosyst. Environ. 114 (2006) 69–85, <https://doi.org/10.1016/j.agee.2005.11.025>.
- [62] P. Singha, P. Das, S. Talukdar, S. Pal, Modeling livelihood vulnerability in erosion and flooding induced river island in Ganges riparian corridor, India, Ecol. Indic. 119 (2020) 106825.
- [63] IPCC, Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2007.
- [64] S.E. Spielman, J. Tuccillo, D.C. Folch, A. Schweikert, R. Davies, N. Wood, E. Tate, Evaluating social vulnerability indicators: criteria and their application to the Social Vulnerability Index, Nat. Hazards 100 (2020) 417–436.
- [65] N.T.T. Pham, D. Nong, A.R. Sathyan, M. Garschagen, Vulnerability assessment of households to flash floods and landslides in the poor upland regions of Vietnam, Clim. Risk Manag. 28 (2020) 100215.
- [66] H.-M. Füssel, R.J. Klein, Climate change vulnerability assessments: an evolution of conceptual thinking, Clim. Change 75 (2006) 301–329.
- [67] S. Das, A. Ghosh, S. Hazra, T. Ghosh, R.S. de Campos, S. Samanta, Linking IPCC AR4 & AR5 frameworks for assessing vulnerability and risk to climate change in the Indian Bengal Delta, Prog. Disaster Sci. 7 (2020) 100110.
- [68] A. Nahman, B.K. Mahumani, W.J. De Lange, Beyond GDP: towards a green economy index, Dev. South Afr. 33 (2016) 215–233.
- [69] N.S. Iyengar, P. Sudarshan, A method of classifying regions from multivariate data, Econ. Polit. Wkly. (1982) 2047–2052.
- [70] B. Chatenoux, P. Peduzzi, Impacts from the 2004 Indian Ocean Tsunami: analysing the potential protecting role of environmental features, Nat. Hazards 40

- (2007) 289–304.
- [71] M.D. Spalding, S. Ruffo, C. Lacambra, I. Meliane, L.Z. Hale, C.C. Shepard, M.W. Beck, The role of ecosystems in coastal protection: adapting to climate change and coastal hazards, *Ocean Coast Manag.* 90 (2014) 50–57.
- [72] H.K. Nibanupudi, R. Shaw, *Mountain Hazards and Disaster Risk Reduction*, Springer, 2015.
- [73] K. Sudmeier-Rieux, T. Arce-Mojica, H.J. Boehmer, N. Doswald, L. Emerton, D.A. Friess, S. Galvin, M. Hagenlocher, H. James, P. Laban, Scientific evidence for ecosystem-based disaster risk reduction, *Nat. Sustain.* 4 (2021) 803–810.
- [74] J.A. Priess, M. Mimler, A.-M. Klein, S. Schwarze, T. Tschardt, I. Steffan-Dewenter, Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems, *Ecol. Appl.* 17 (2007) 407–417.
- [75] S. Lavorel, M.D. Flannigan, E.F. Lambin, M.C. Scholes, Vulnerability of land systems to fire: interactions among humans, climate, the atmosphere, and ecosystems, *Mitig. Adapt. Strategies Glob. Change* 12 (2007) 33–53.
- [76] M.J. Metzger, M.D.A. Rounsevell, L. Acosta-Michlik, R. Leemans, D. Schröter, The vulnerability of ecosystem services to land use change, *Agric. Ecosyst. Environ.* 114 (2006) 69–85.
- [77] J.J. Lawler, D.J. Lewis, E. Nelson, A.J. Plantinga, S. Polasky, J.C. Withey, D.P. Helmers, S. Martinuzzi, D. Pennington, V.C. Radeloff, Projected land-use change impacts on ecosystem services in the United States, *Proc. Natl. Acad. Sci. USA* 111 (2014) 7492–7497.
- [78] *Millennium Ecosystem Assessment, Millennium Ecosystem Assessment: Ecosystems and Human Well-Being: Synthesis*, Island Press, Washington, DC, 2005.
- [79] J.M.J. Travis, Climate change and habitat destruction: a deadly anthropogenic cocktail, *Proc. R. Soc. Lond. B Biol. Sci.* 270 (2003) 467–473.
- [80] R.L. Chazdon, Beyond deforestation: restoring forests and ecosystem services on degraded lands, *Science* 320 (2008) 1458–1460.
- [81] J.P. Rodríguez, T.D. Beard Jr, E.M. Bennett, G.S. Cumming, S.J. Cork, J. Agard, A.P. Dobson, G.D. Peterson, Trade-offs across space, time, and ecosystem services, *Ecol. Soc.* 11 (2006).
- [82] C. Raudsepp-Hearne, G.D. Peterson, E.M. Bennett, Ecosystem service bundles for analyzing tradeoffs in diverse landscapes, *Proc. Natl. Acad. Sci. USA* 107 (2010) 5242–5247.
- [83] K.A. Farley, E.G. Jobbágy, R.B. Jackson, Effects of afforestation on water yield: a global synthesis with implications for policy, *Global Change Biol.* 11 (2005) 1565–1576.
- [84] R.B. Jackson, E.G. Jobbágy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. Le Maitre, B.A. McCarl, B.C. Murray, Trading water for carbon with biological carbon sequestration, *Science* 310 (2005) 1944–1947.
- [85] M.-S. Attems, T. Thaler, E. Genovese, S. Fuchs, Implementation of property-level flood risk adaptation (PLFRA) measures: choices and decisions, *WIREs Water* 7 (2020) e1404, <https://doi.org/10.1002/wat2.1404>.
- [86] H.S. Kim, G.J. Park, S.D. Kim, M.H. Choi, M.J. Park, J.Y. Yoon, Assessment of flood vulnerability considering climate change and large-scale river restoration project, *J. Korean Soc. Hazard Mitig.* 12 (2012) 107–113, <https://doi.org/10.9798/KOSHAM.2012.12.2.107>.
- [87] B.P. Bhandari, S. Dhakal, Evolutional characteristics of debris flow in the Siwalik hills of Nepal, *Int. J. Geosci.* 10 (2019) 1049–1067, <https://doi.org/10.4236/ijg.2019.1012060>.
- [88] B.K. Pokharel, D.R. Uprety, R.R. Niraula, P.R. Pokharel, An assessment of the impact of silviculture and forest management regimes to forest cover change in the Churia region during 1992 to 2014, *Banko Janakari* (2018) 38–44, <https://doi.org/10.3126/banko.v27i3.20540>.
- [89] R.R. Aryal, H.L. Shrestha, S. Khanal, Using Landsat data for assessing forest cover change and fragmentation in Laljhadi corridor of Kanchanpur district, Nepal, *Banko Janakari* 21 (2011) 40–44, <https://doi.org/10.3126/banko.v21i2.9142>.
- [90] K. Bhattarai, D. Conway, M. Yousef, Determinants of deforestation in Nepal's central development region, *J. Environ. Manag.* 91 (2009) 471–488, <https://doi.org/10.1016/j.jenvman.2009.09.016>.
- [91] M. Ghimire, Historical land covers change in the chure-Tarai landscape in the last six decades: drivers and environmental consequences, in: A. Li, W. Deng, W. Zhao (Eds.), *Land Cover Change its Eco-Environ. Responses Nepal*, Springer, Singapore, 2017, pp. 109–147, https://doi.org/10.1007/978-981-10-2890-8_5.
- [92] S. Rijal, B. Rimal, S. Sloan, Flood hazard mapping of a rapidly urbanizing city in the Foothills (Birendranagar, surkhet) of Nepal, *Land* 7 (2018) 60, <https://doi.org/10.3390/land7020060>.