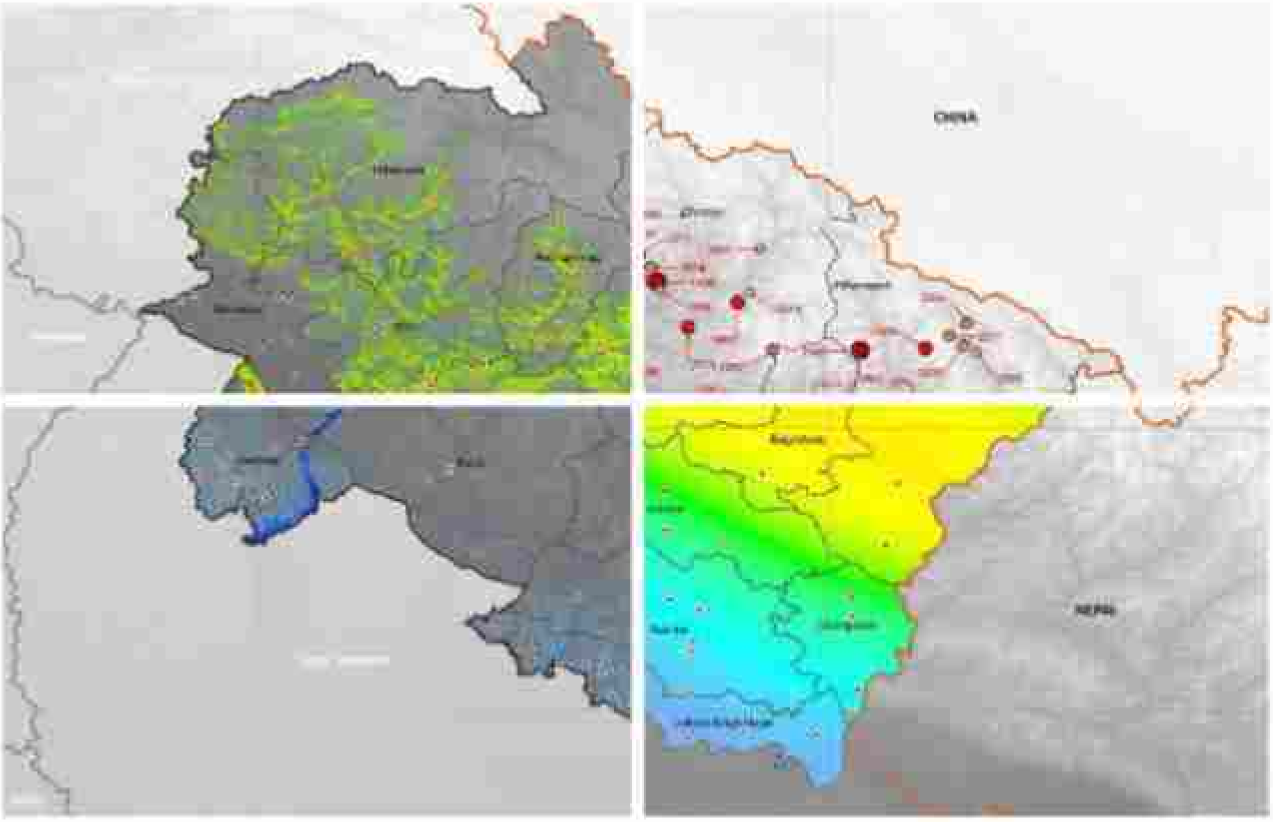
In Collaboration with the Earth Observatory Singapore

Uttarakhand Disaster Recovery Project

Disaster Risk Assessment of Uttarakhand



State Level Assessment

Volume 3A

Project Implementation Unit TA & CBDRM

January 2019

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DISASTER RISK ASSESSMENT OF UTTARAKHAND

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And

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M/s Asian Institute of Technology, Thailand

M/s Evaluacion de Riesgos Naturales, Mexico DF

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Uttarakhand Disaster Recovery Project

Disaster Risk Assessment of Uttarakhand

State Level Assessment

Prepared for	Project Implementation Unit TA & CBDRM
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Team Leader	Tom Burkitt
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CONTENTS

3.1 Baseline Exposure Profile

This section will summarise the state of Uttarakhand as a whole, in terms of the baseline value (human and economic) which could potentially be exposed to the hazards under consideration. Uttarakhand's location is shown in the inset map to the right, relative to India's other states and international neighbours.

To illustrate the spatial distribution of this baseline exposure value, a series of maps are presented in the following sections, grouping exposure into five 'portfolios': population (Volume 3.1.1), residential buildings (Volume 3.1.2), critical buildings (Volume 3.1.3), transportation infrastructure (Volume 3.1.4), power infrastructure (Volume 3.1.5), and various economic sectors (Volume 3.1.6).

As an initial summary, the figures below summarise pertinent demographic properties of the state of Uttarakhand. All figures are derived from the 2011 Census, noting that 2017 projections for population and number of households are based on the observed growth rates between the 2001 and 2011 Censuses.

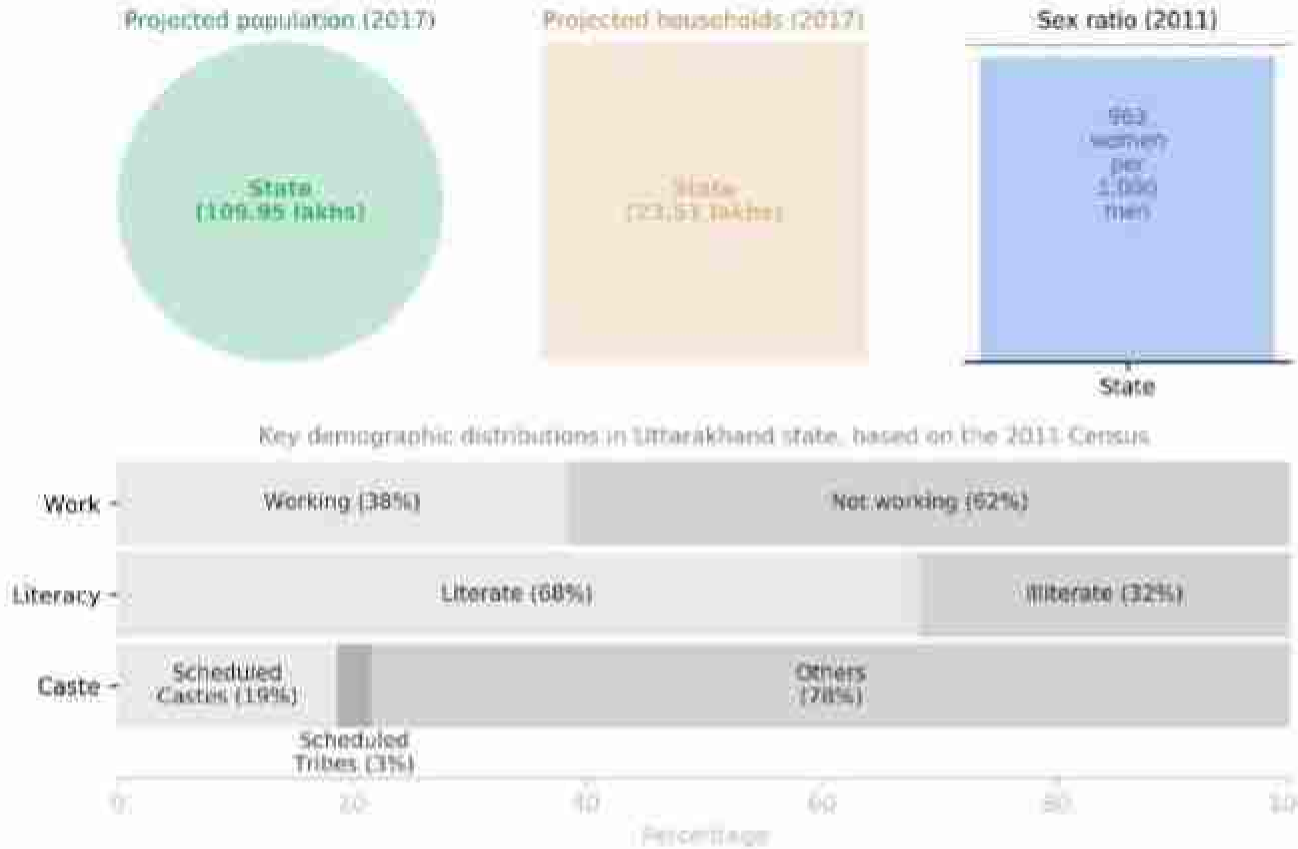

Figure 3.1. Baseline demographic statistics extracted from the 2011 Census for Uttarakhand

On the following page, a selection of baseline household statistics from the 2011 Census are visualised for the state in Figure 3.2, providing insight into the condition and size of its buildings, the most common building materials (for walls), and the general distribution of the population.

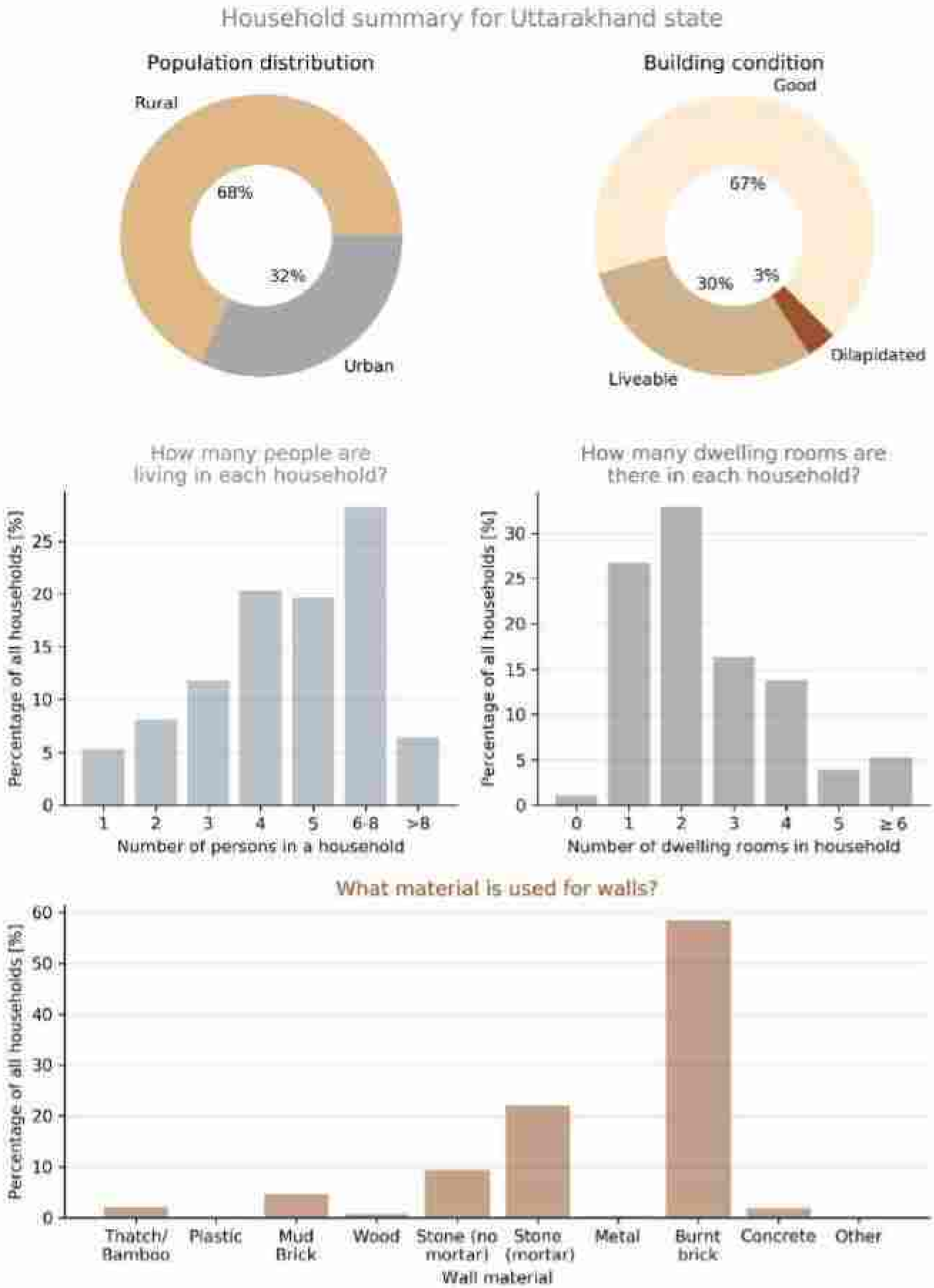

Figure 3.2: Baseline household statistics extracted from the 2011 Census for Uttarakhand

As discussed in detail in Volume 1, social vulnerability was assessed for the whole state, using a combination of indicators from the 2011 Census. These provide a comprehensive assessment of likely social vulnerability in each village and town in the State, by looking at indicators at three levels: individual (e.g. percentage of population illiterate or not working), household (e.g. percentage of households with access to phone or indoor latrine) and community (e.g. distance to nearest city or hospital). Figure 3.3 maps the results of this assessment across the whole state, in terms of the relative rankings of all settlements (towns and villages).

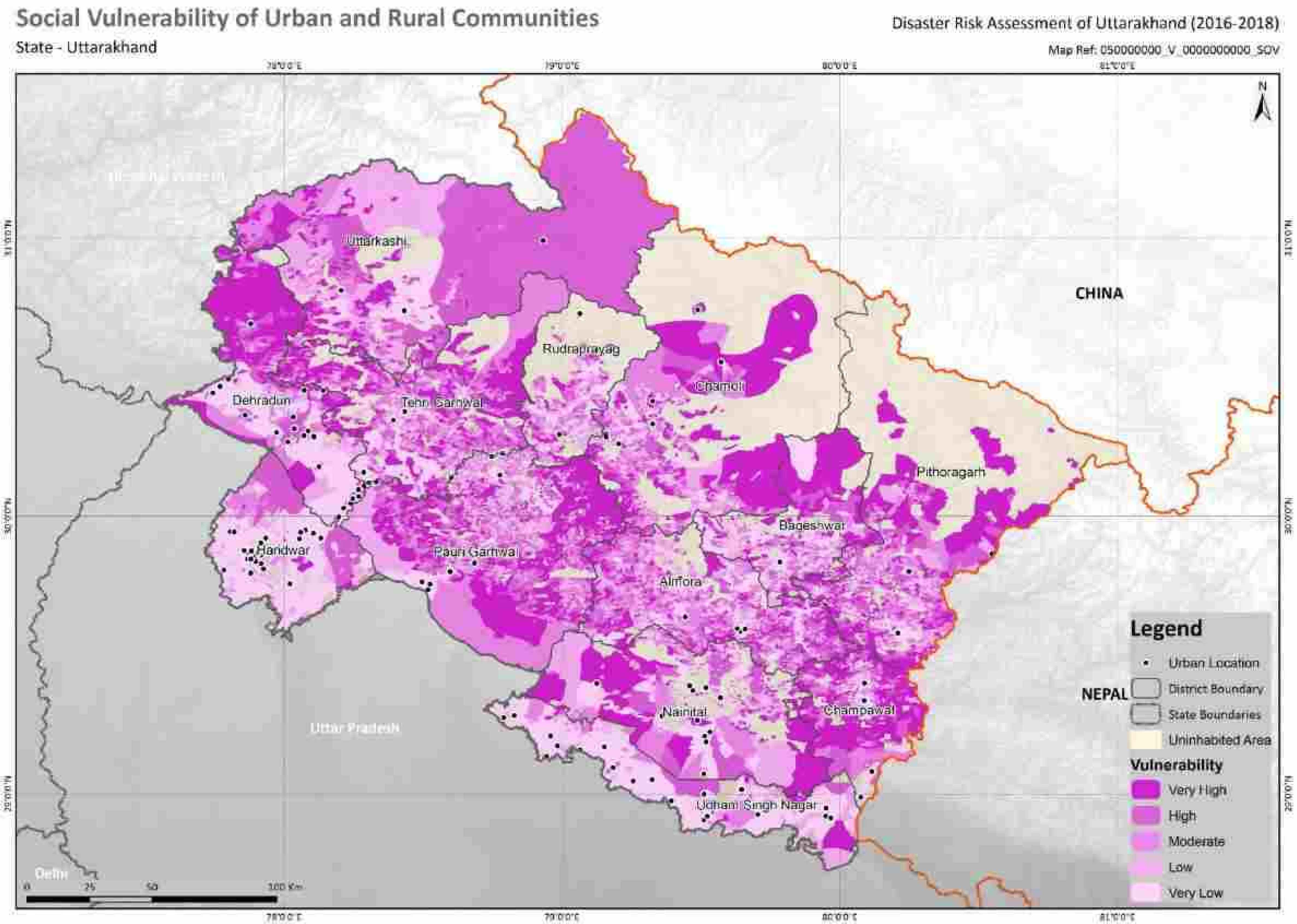

Figure 3.3: Baseline community socio-economic vulnerability, based on ranking of urban and rural settlements

3.1.1 Population

Figure 3.4 shows the population density distribution across the state, based on data from the 2011 Census.

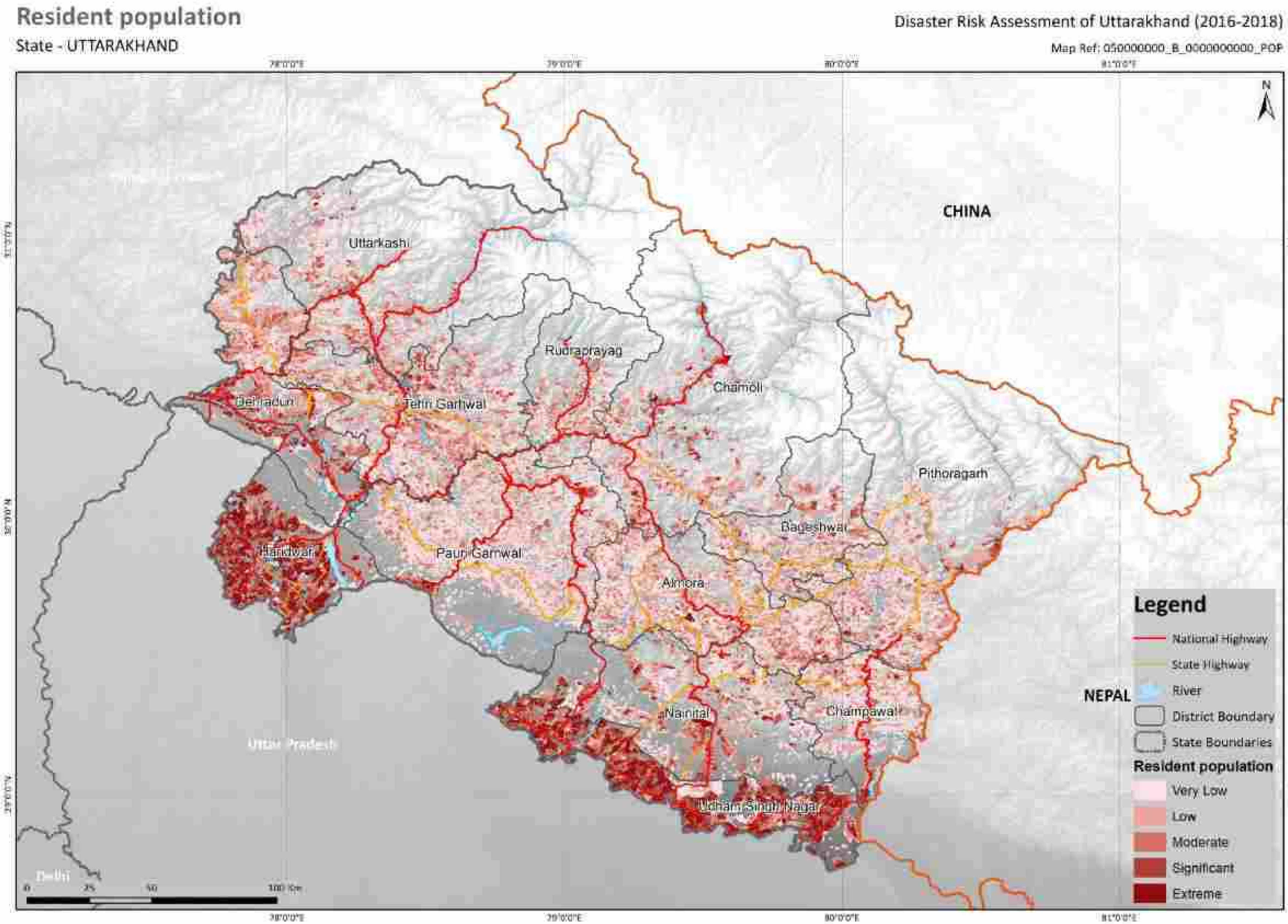

Figure 3.4: Population density distribution in Uttarakhand

Figure 3.5 shows the distribution of annual tourist numbers across the state, as well as the primary areas of tourism activity (yellow polygons).

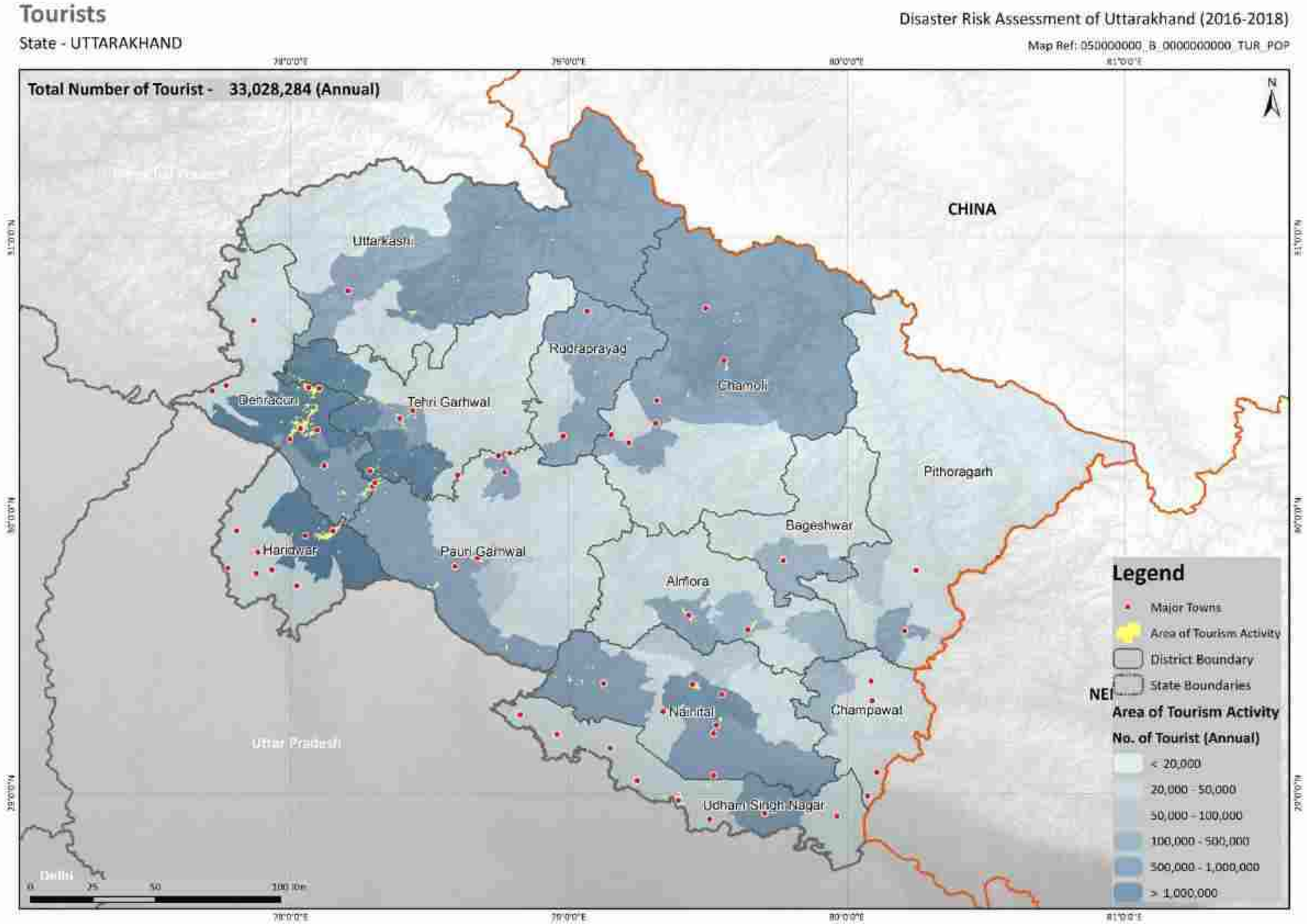

Figure 3.5: Annual tourist population distribution in Uttarakhand

3.1.2 Residential buildings

Figure 3.6 shows the residential buildings which have been digitised in Uttarakhand, as well the total expected number of buildings (based on projections made using the two most recent Censuses).

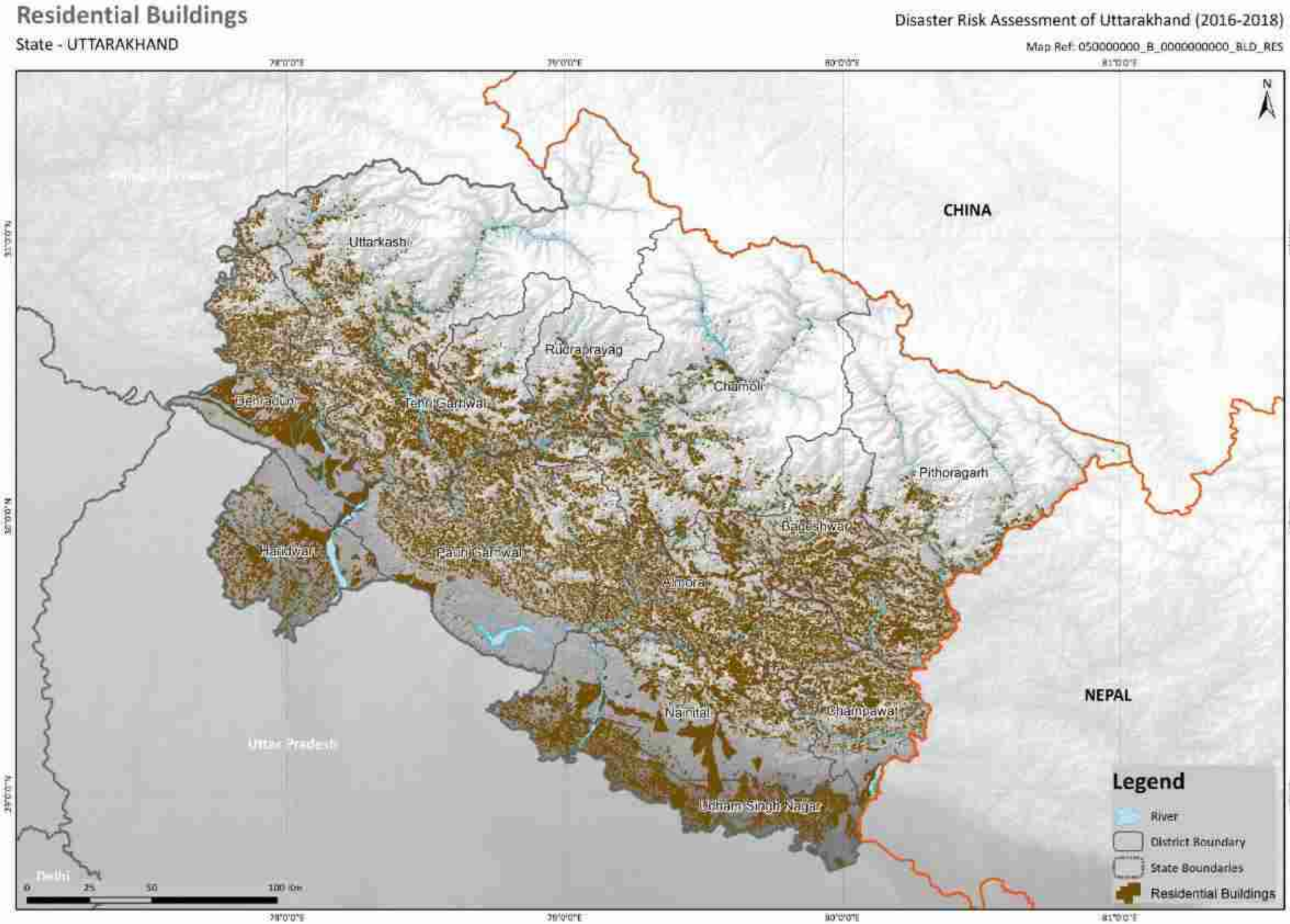

Figure 3.6: Digitised residential buildings in Uttarakhand

3.1.3 Critical buildings

Figure 3.7 shows the locations of various critical buildings in Uttarakhand (categorised into four classes), which are all of particular importance during disaster response and recovery.

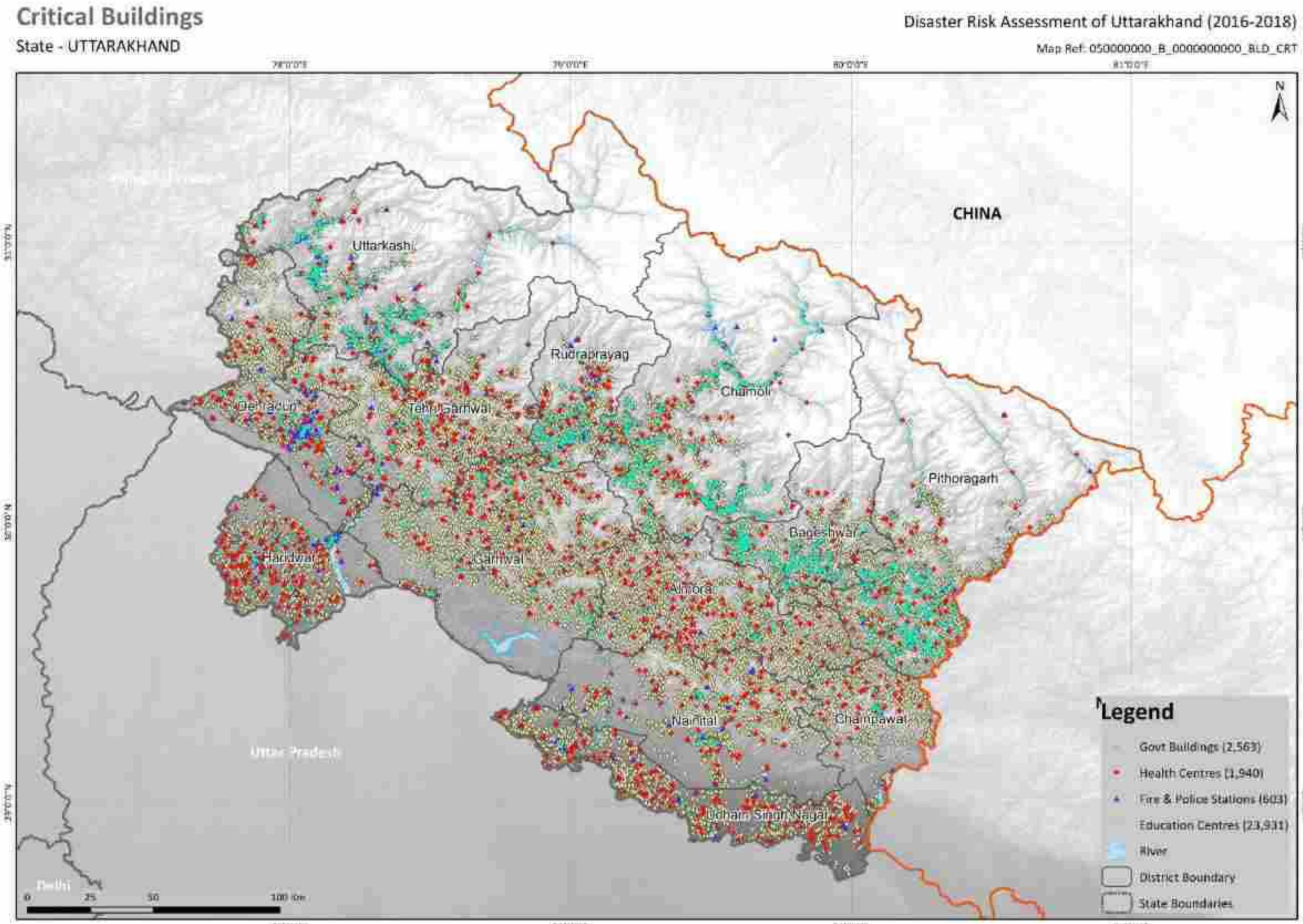

Figure 3.7: Critical buildings in Uttarakhand

3.1.4 Transportation infrastructure

Figure 3.8 shows the transportation infrastructure available in Uttarakhand, covering road, rail and air transport facilities.

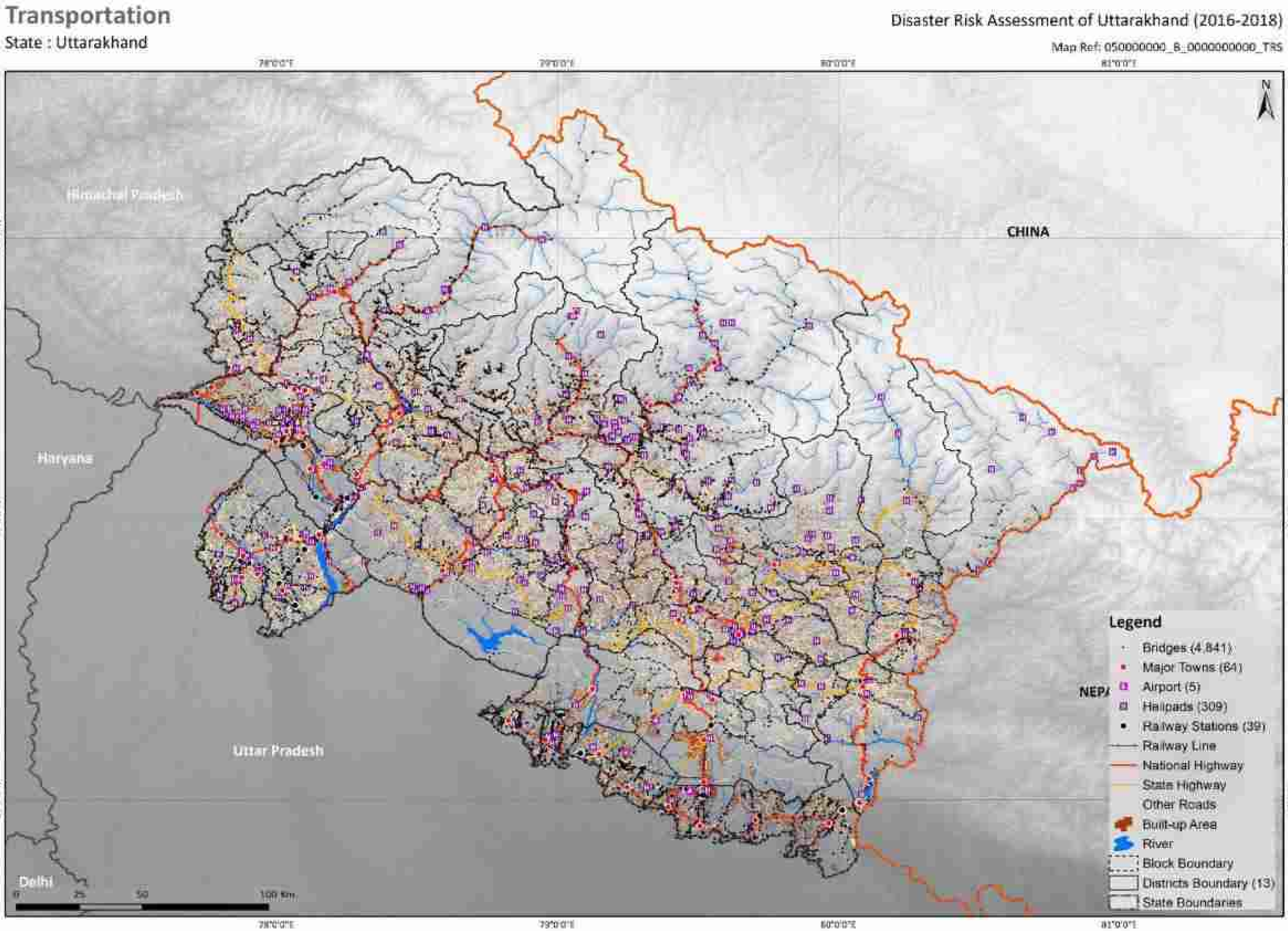

Figure 3.8: Transportation infrastructure in Uttarakhand

3.1.5 Power infrastructure

Figure 3.9 shows the power infrastructure present in Uttarakhand, covering transmission and distribution substations, hydropower stations, and dams.

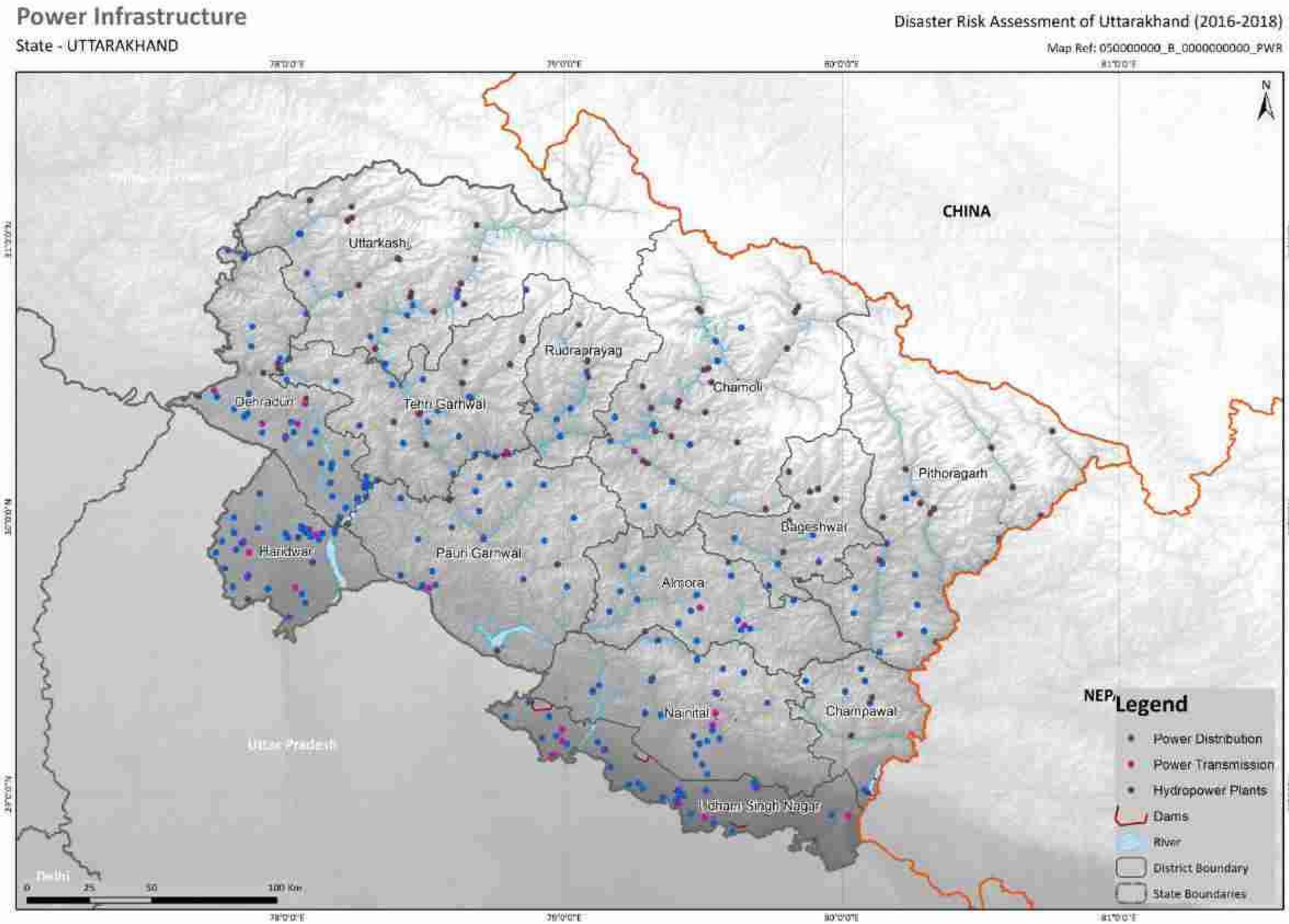

Figure 3.9: Power infrastructure in Uttarakhand

3.1.6 Economic sectors

This section will present a range of maps showing the spatial distribution of value across Uttarakhand's various economic sectors. Figure 3.10 visualises the variation in baseline agricultural exposure within Uttarakhand, in terms of the value (capital investment plus annual production) present in each of the state's blocks, as well as showing the outlines of the agricultural fields mapped across the entire state.

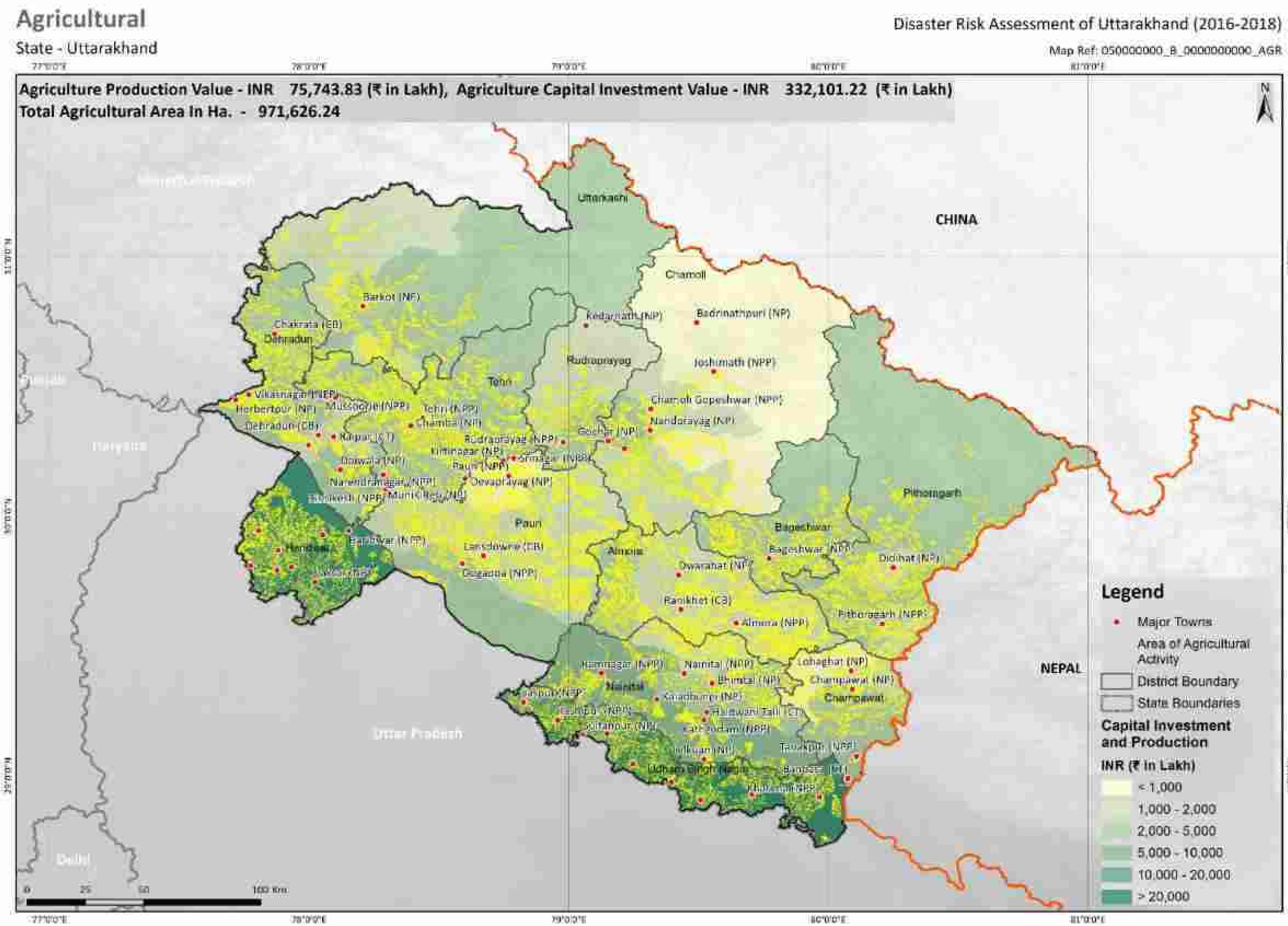

Figure 3.10: Baseline agricultural value in Uttarakhand

Figure 3.11 visualises the variation in baseline horticultural and livestock exposure within Uttarakhand, in terms of the sum of each sector's annual production value in each of the state's blocks.

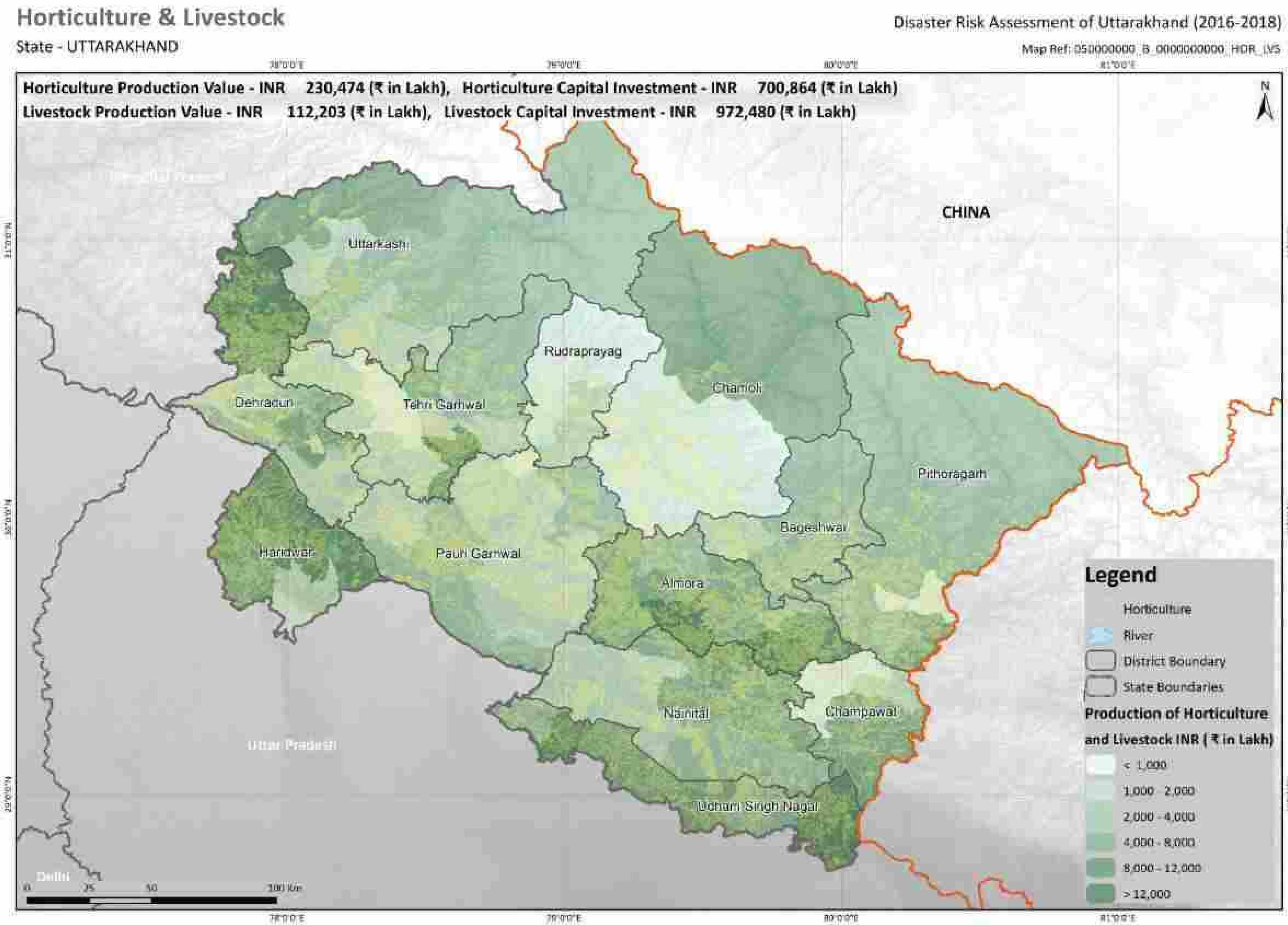

Figure 3.11: Baseline horticultural and livestock value in Uttarakhand

Figure 3.12 shows the distribution of baseline industrial, commercial and mining value across Uttarakhand, accounting for both capital investment and annual production value present in each of the state's blocks, as well as showing the locations of dedicated industrial areas, concentrated commercial areas and mines.

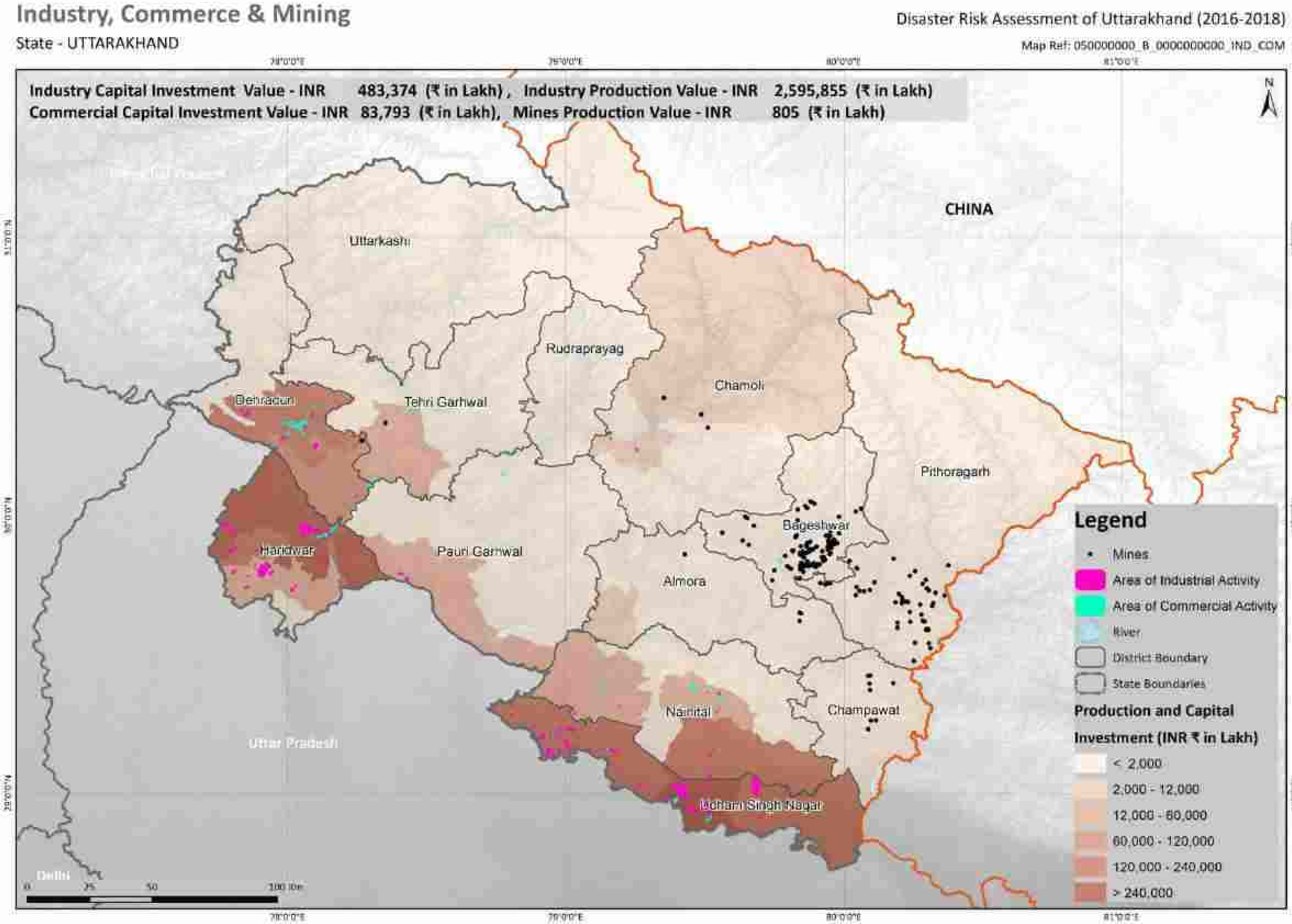

Figure 3.12: Distribution of baseline industrial, commercial and mining value (including capital investment and annual production) across Uttarakhand

Figure 3.13 shows the distribution of potential (annual) tourism revenue across Uttarakhand (by block), as well as indicating the state-wide total in the map label.

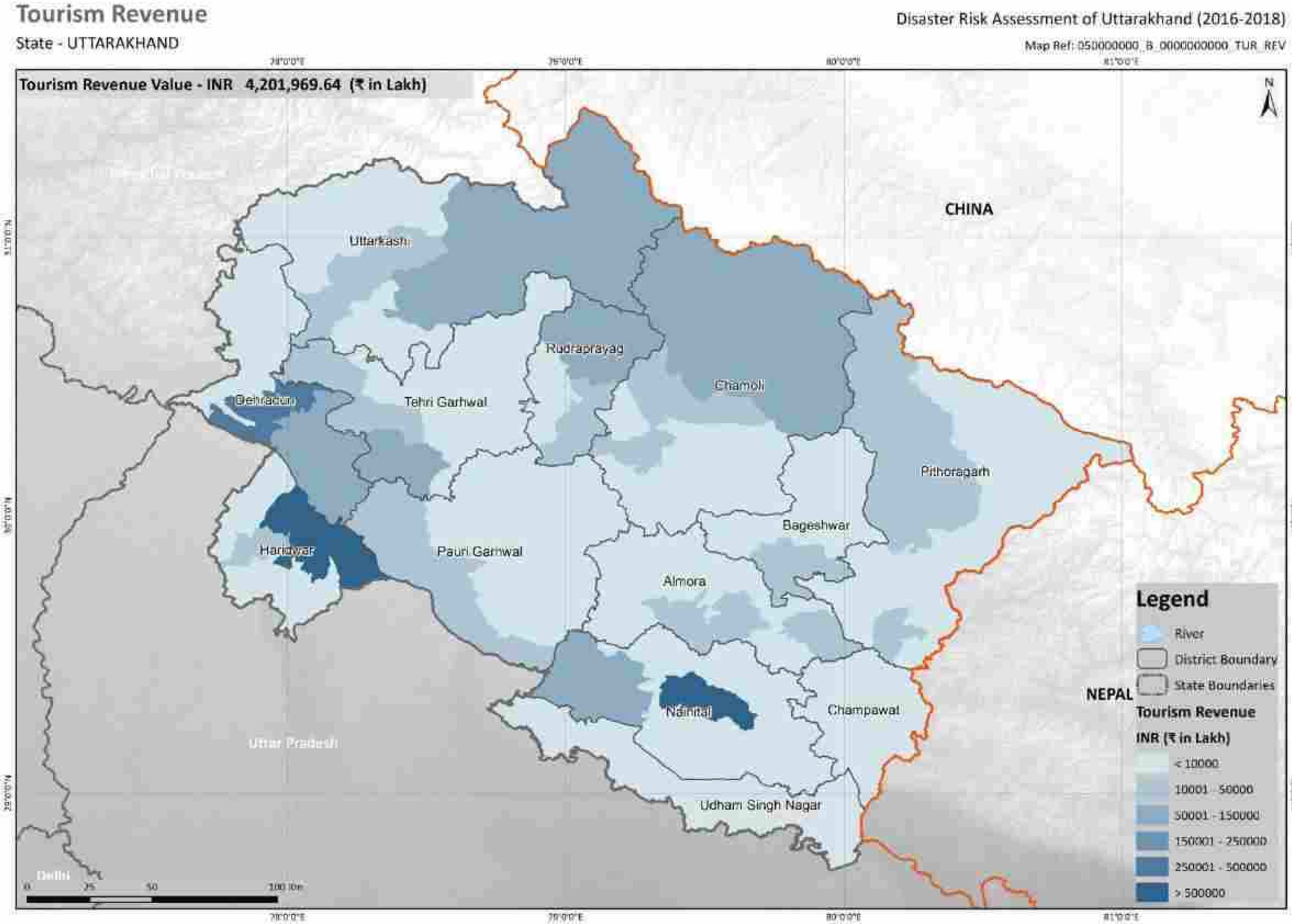

Figure 3.13: Potential tourism revenue in Uttarakhand

3.2 Multi-hazard Assessment – Earthquakes & Fluvial Floods

/ Loss Profile

This section provides a summary of the average annual economic losses and the potential fatalities resulting from the probabilistic assessment of Earthquake and Fluvial Flood risk. Following the summary, the exposure and losses are presented in greater detail for each hazard.

Figure 3.14 shows the breakdown of the combined Economic AAL, in terms of the hazard type (inner ring) and portfolio (outer ring). It is clear that at the State level, losses due to earthquakes are far more significant than those due to fluvial floods, over the long term.

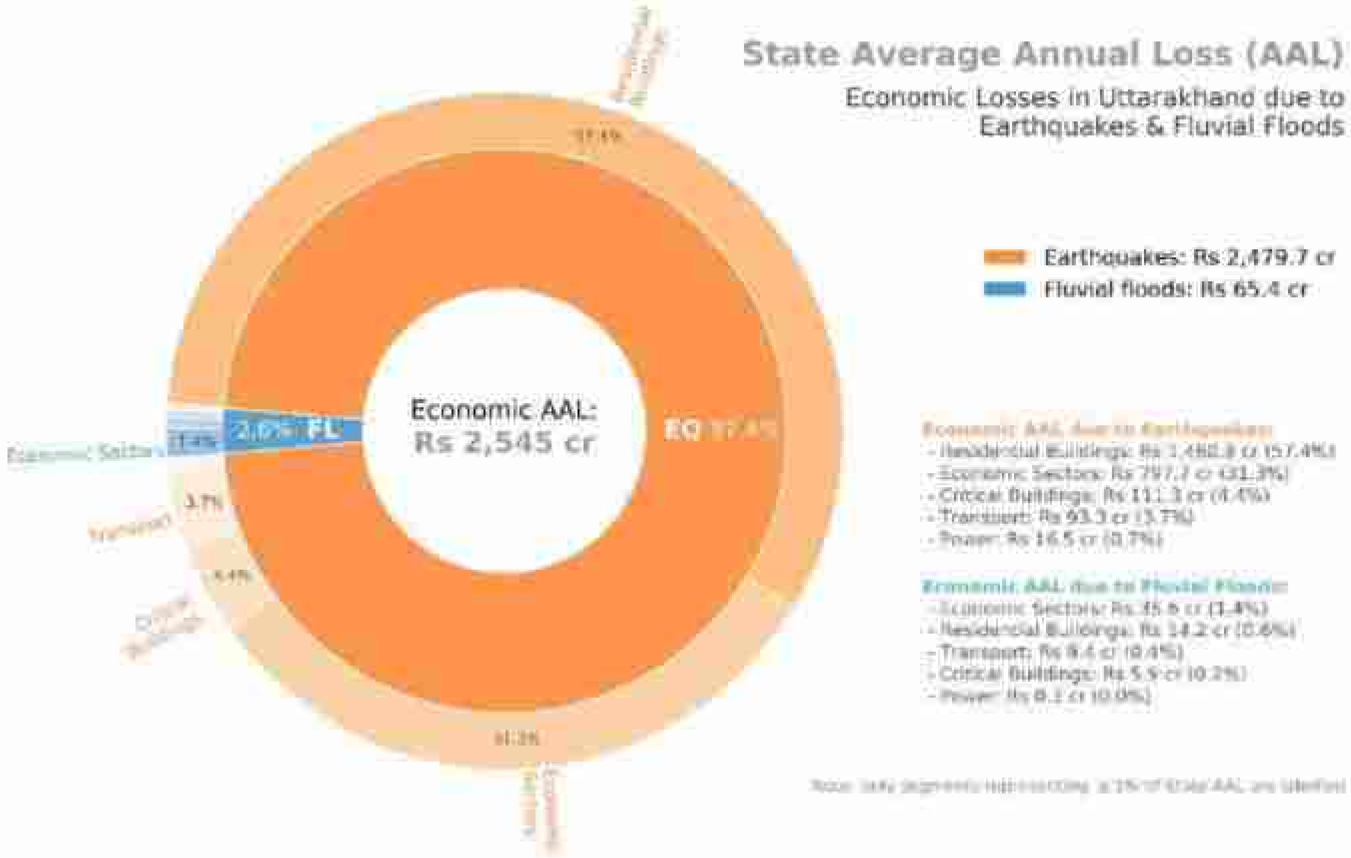

Figure 3.14: Breakdown of total Annual Average Loss, by hazard and portfolio

Figure 3.15 presents a ranking of all Districts and Blocks within the State, in terms of their total Average Annual Loss (AAL), including losses due to both earthquakes and fluvial floods.

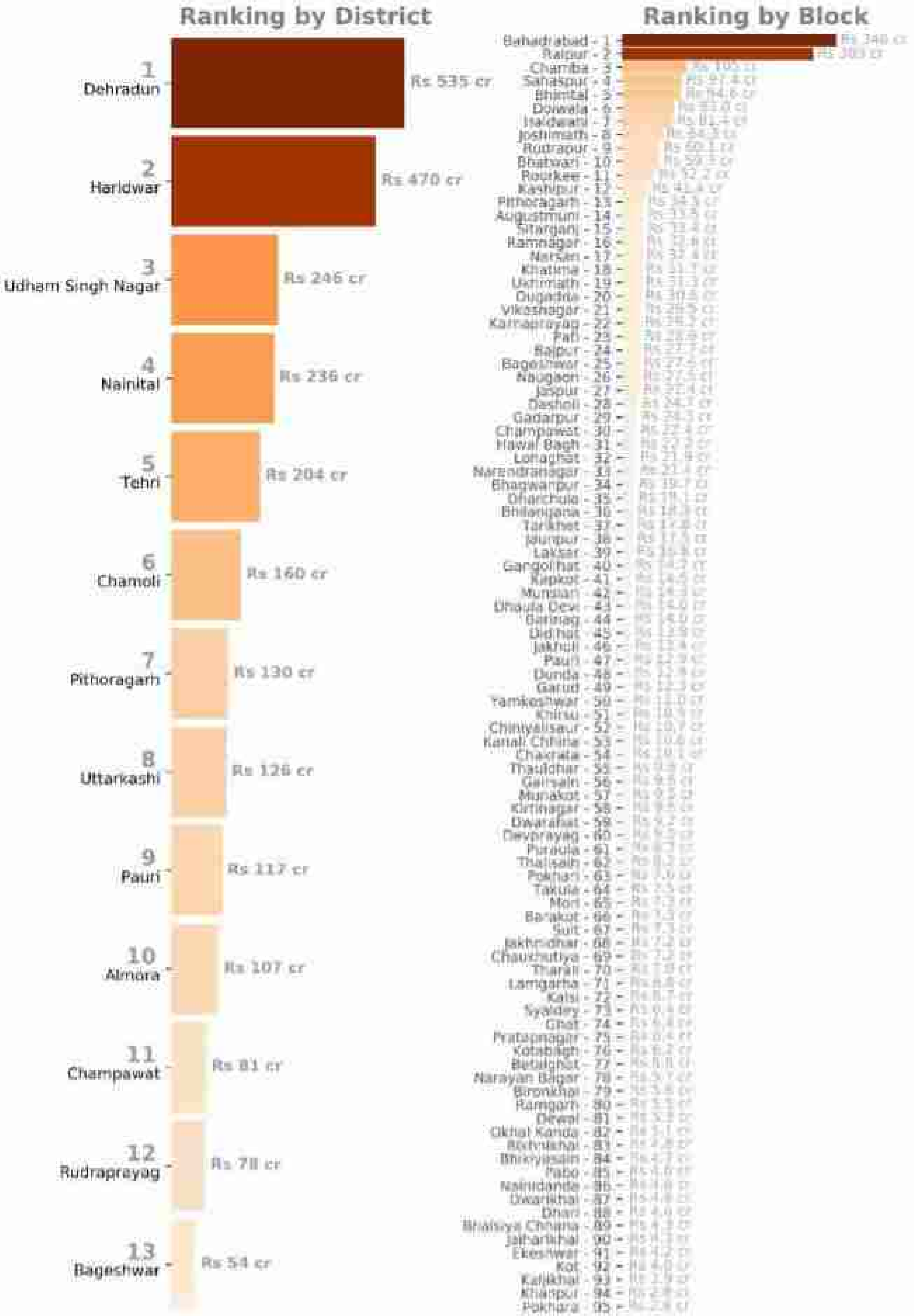

Figure 3.15: Ranking of all Districts and Blocks in the state, based on total combined Average Annual Loss (Economic)

The spatial distribution of these combined Average Annual Loss (AAL) values are mapped in Figure 3.16, in terms of block totals across the state.

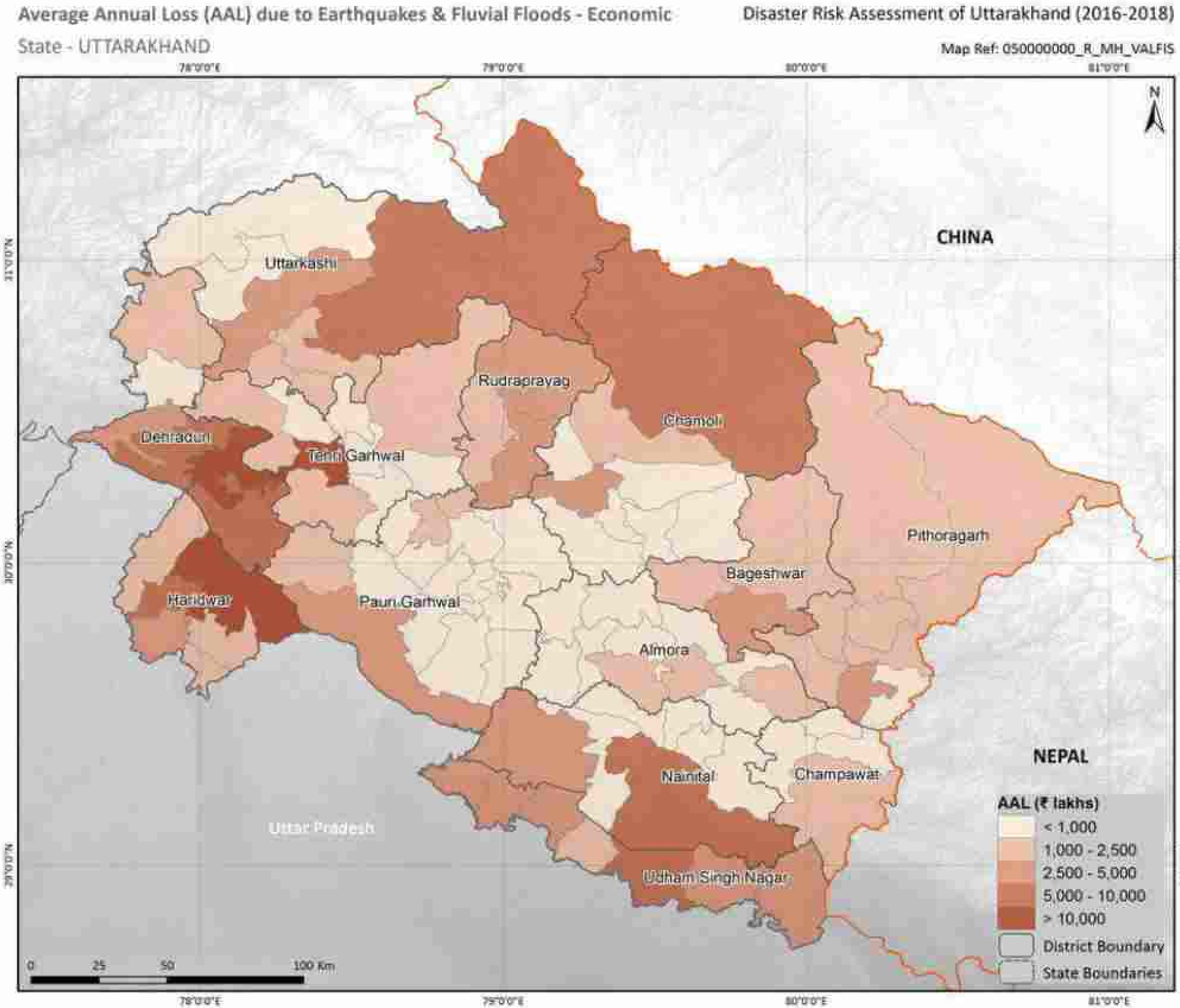

Figure 3.16: Spatial distribution of combined Average Annual Loss (AAL) of economic assets in Uttarakhand, accounting for both earthquakes and fluvial floods

Figure 3.17 shows the breakdown of the combined Average Annual Fatalities (lives lost), in terms of the hazard type (inner ring) and the residency of the affected population (outer ring).

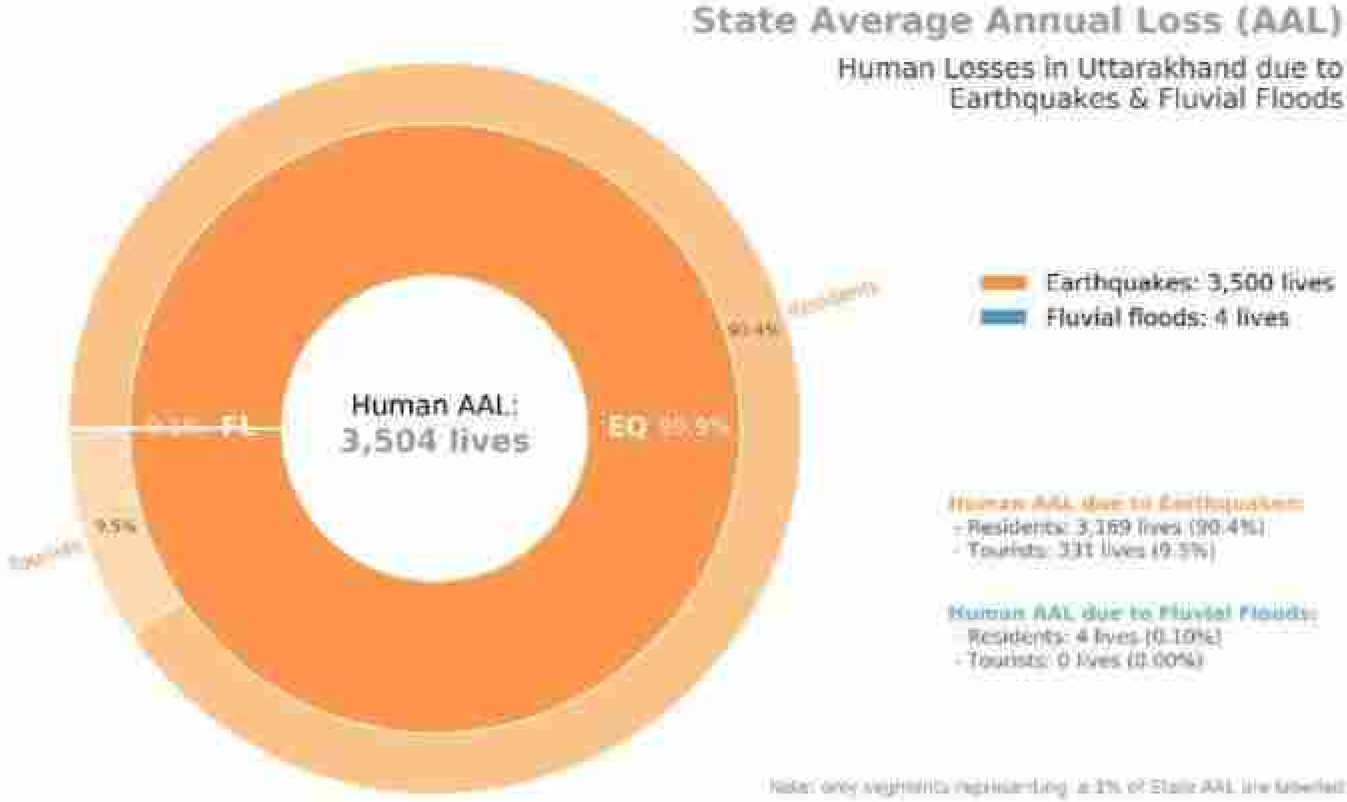

Figure 3.17: Breakdown of estimated loss of life, by hazard, Division and terrain type

Figure 3.18 presents a ranking of all Districts and Blocks within the State, in terms of their total combined Average Annual Loss (AAL) of life, as a result of both earthquakes and fluvial floods.

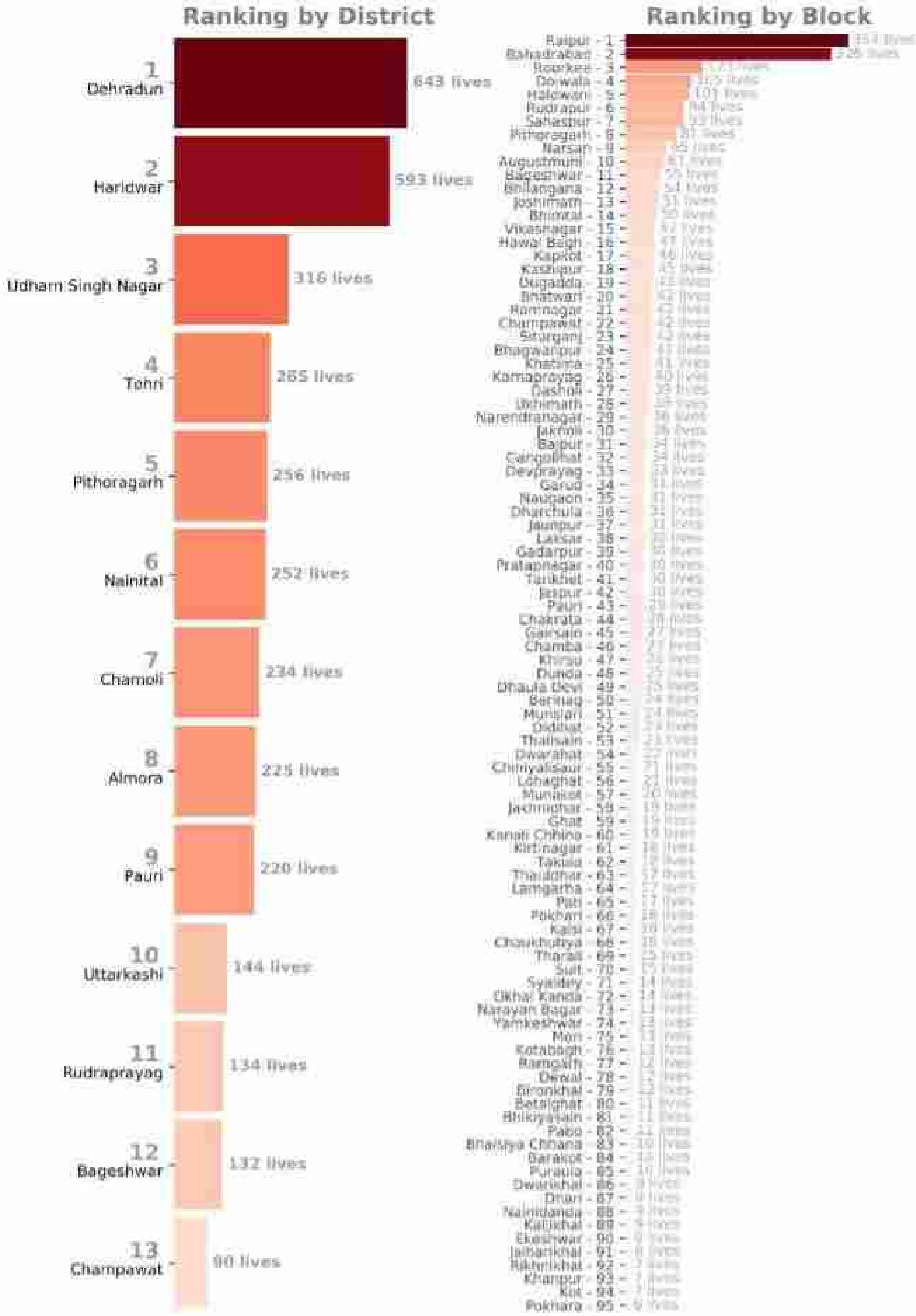

Figure 3.18: Ranking of all Districts and Blocks in the state, based on total combined Average Annual Loss (Human)

The spatial distribution of these Average Annual Fatalities across the state is illustrated in Figure 3.19, in terms of block totals considering both residents and tourists.

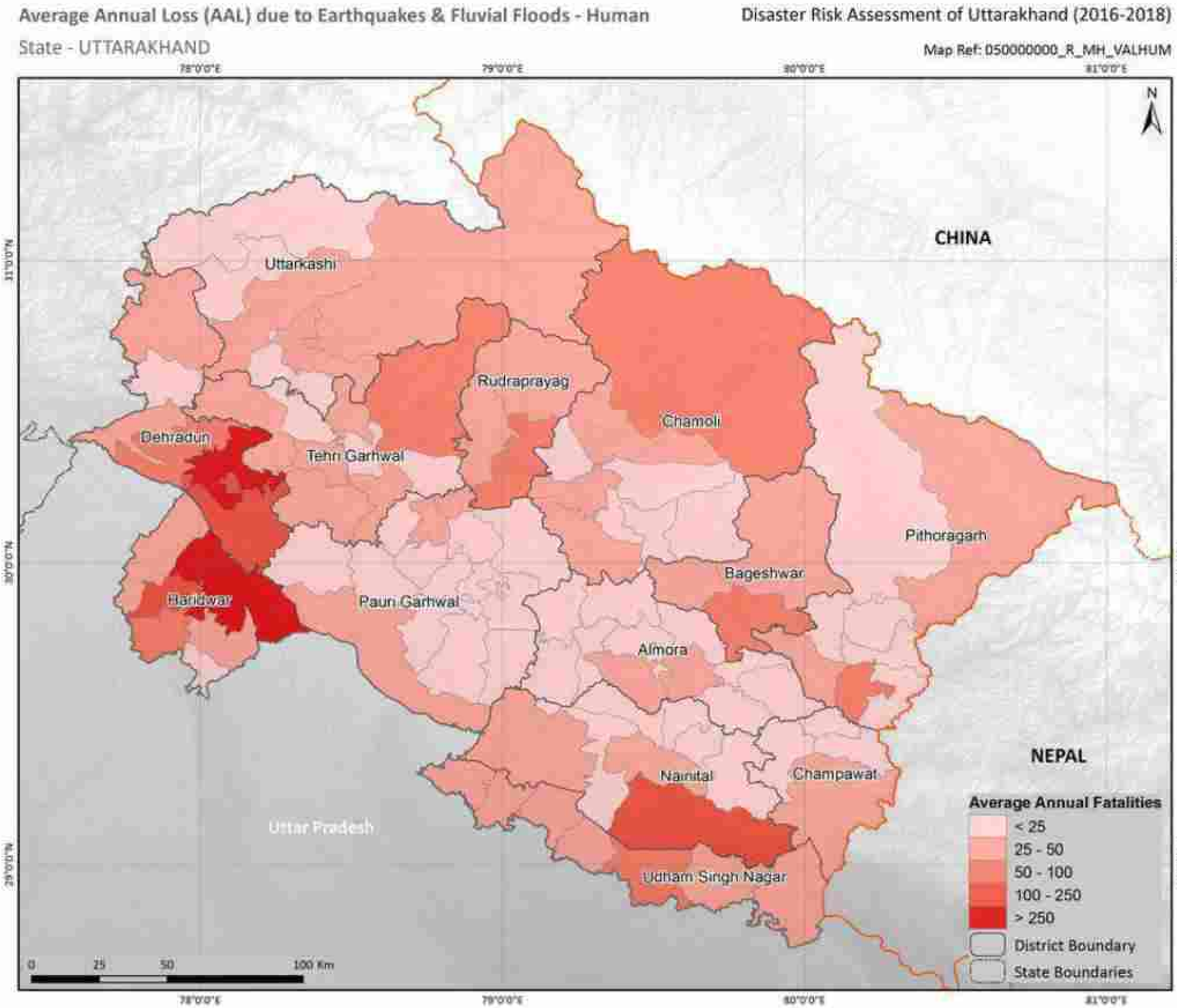

Figure 3.19: Spatial distribution of combined Average Annual Loss (AAL) of human lives in Uttarakhand, accounting for both earthquakes and fluvial floods

3.3 Earthquakes

Hazard Profile

Seismicity along the Himalayan arc is a consequence of the ongoing continent-to-continent collision between the Indian and Eurasian plates, with the state of Uttarakhand exposed to earthquakes occurring in the Himalayan Thrust zone.

At the time of writing, 96 historical earthquakes with epicentres within the state boundaries had so far been recorded. Table 3.1 summarises the largest and the most recent of these, while the map in Volume 3.3.1 presents all historical earthquake events which have been recorded in the state of Uttarakhand.

Table 3.1: Summary of the largest and most recent earthquake events recorded in the state

Historical earthquake event	Date	Magnitude
Largest earthquake recorded	1991	6.8
Most recent earthquake recorded	06/12/2017	5.1

Based on the probabilistic seismic hazard assessment carried out for Uttarakhand (see Volume 1, Chapter 2 for a full description of the methodology), maps of the predicted seismic intensity (in terms of Peak Ground Acceleration) have been generated for the whole state, for nine different return periods. The ranges of PGA values estimated for all of these return periods are summarised in Figure 3.20, while the following sections (Volumes 3.3.2 - 3.3.5) present the maps for four of the return periods (10, 100, 475 and 1,000 years).

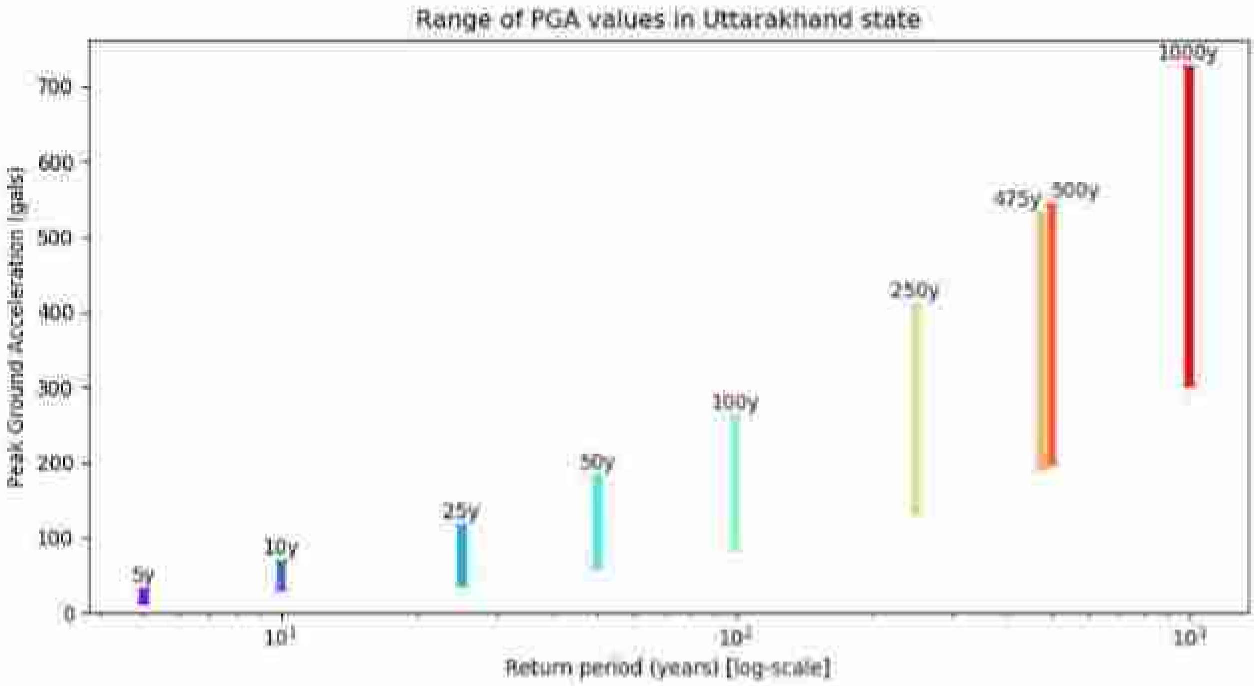

Figure 3.20: Ranges of estimated PGA values (cm/s²) in Uttarakhand, for all return periods

For each district and each block in the state, the median PGA values (for the 475 year return period) were used to develop ranking tables. These are presented in Figure 3.21 (following page), with the district ranking on the left and blocks on the right.

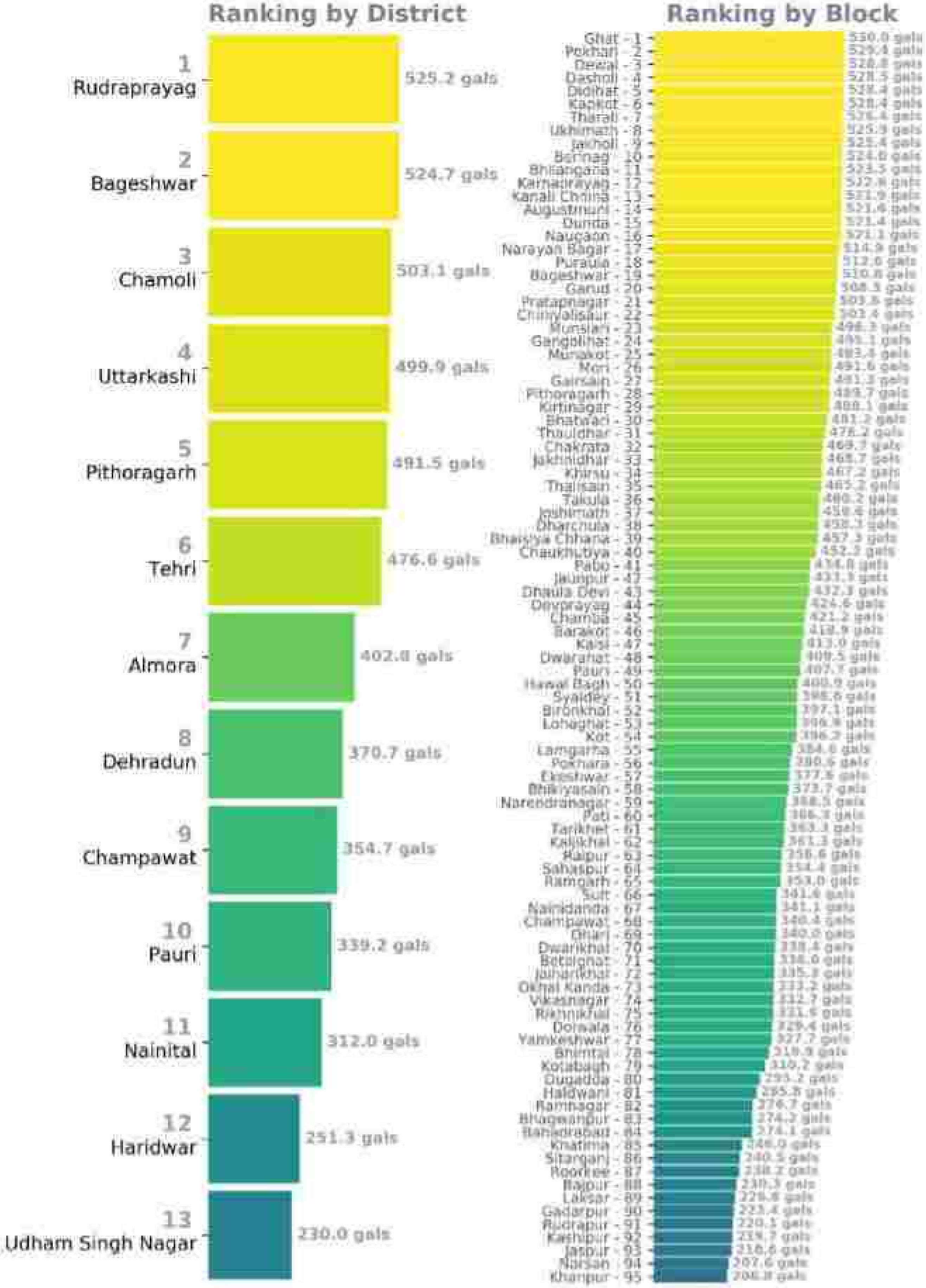

Figure 3.21: Ranking of districts (left) and blocks (right) in state, based on median PGA values (for the 475 year return period)

These PGA values were also converted into intensity classes (in the Modified Mercalli Intensity scale), based on the equation developed by Ramalingeswara et al. (1982) for the Indian region. The distribution of these intensity classes across the state is presented in Figure 3.22 for all return periods investigated, on the basis of eight classes ranging from 'Very Low' to 'Extreme' intensities. For example, the plot shows that for the 5 year return period, approximately 24% of the state is in the 'Low' class, with the remaining 76% in the 'Moderate' intensity class.

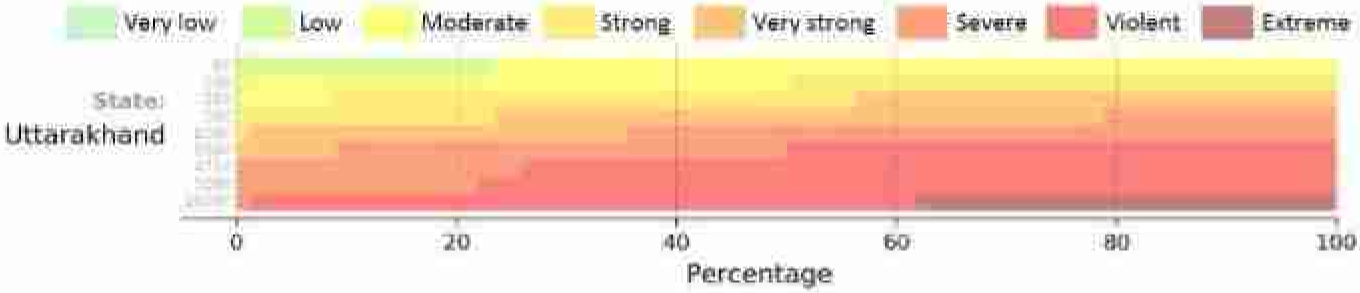

Figure 3.22 Seismic intensity class distribution in the state of Uttarakhand

3.3.1 Map of historical earthquakes

The map in Figure 3.23 shows the 96 historical earthquakes which had so far been recorded in the state of Uttarakhand at the time of writing.

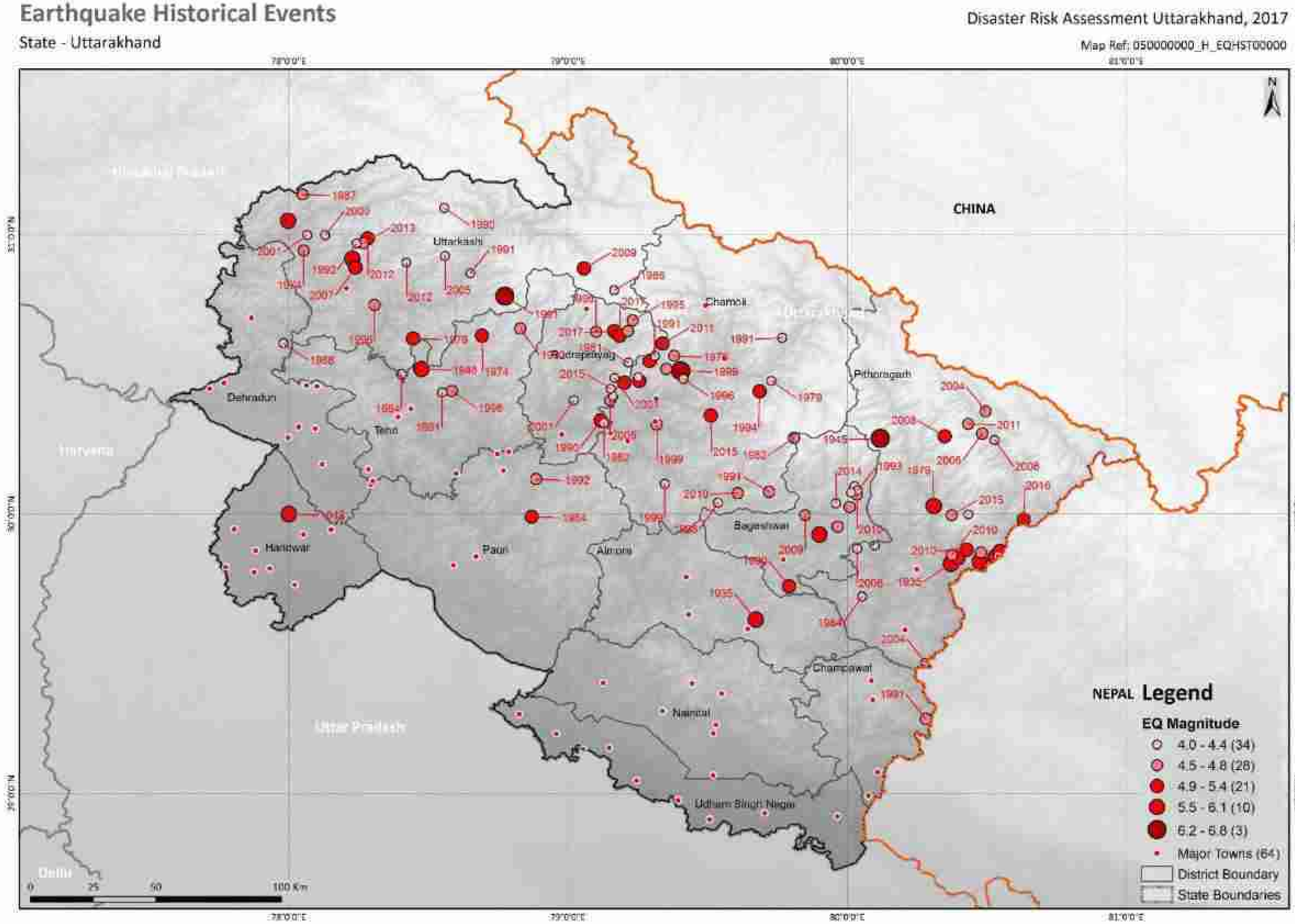

Figure 3.23: Historical earthquake events recorded in Uttarakhand

3.3.2 Seismic hazard map: 10 year return period

Seismic hazard intensities with a 10 year return period are mapped for Uttarakhand in Figure 3.24, showing a Peak Ground Acceleration ranging between 29.4 - 67.4 cm/s².

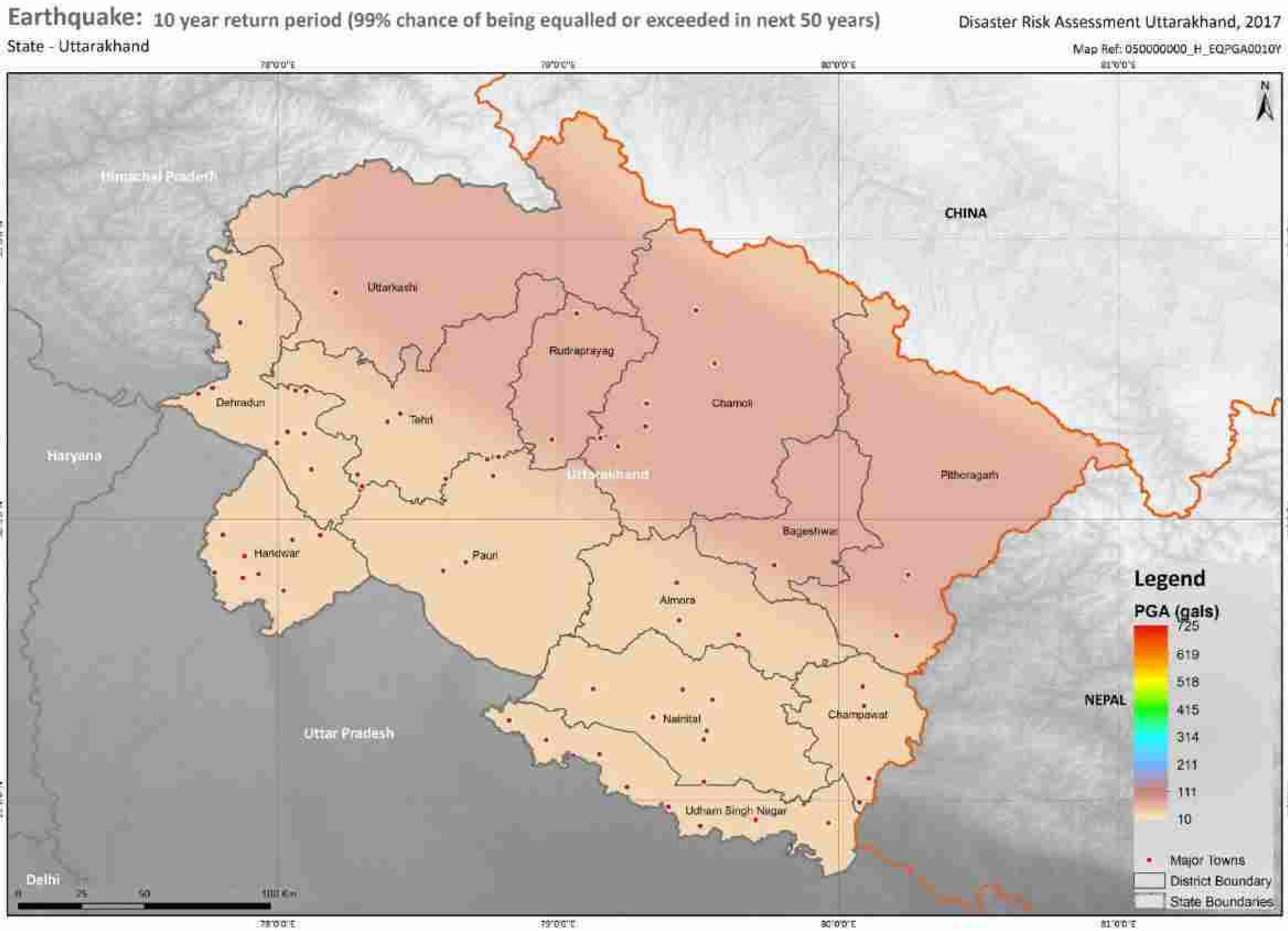

Figure 3.24: Seismic hazard map showing estimated PGA values (cm/s²) in Uttarakhand with a 10 year return period

3.3.3 Seismic hazard map: 100 year return period

Seismic hazard intensities with a 100 year return period are mapped for Uttarakhand in Figure 3.25, showing a Peak Ground Acceleration ranging between 84.4 - 260.2 cm/s^2.

Earthquake: 100 year return period (40% chance of being equalled or exceeded in next 50 years)

State - Uttarakhand

Disaster Risk Assessment Uttarakhand, 2017

Map Ref: 050000000_H_EQPGA0100Y

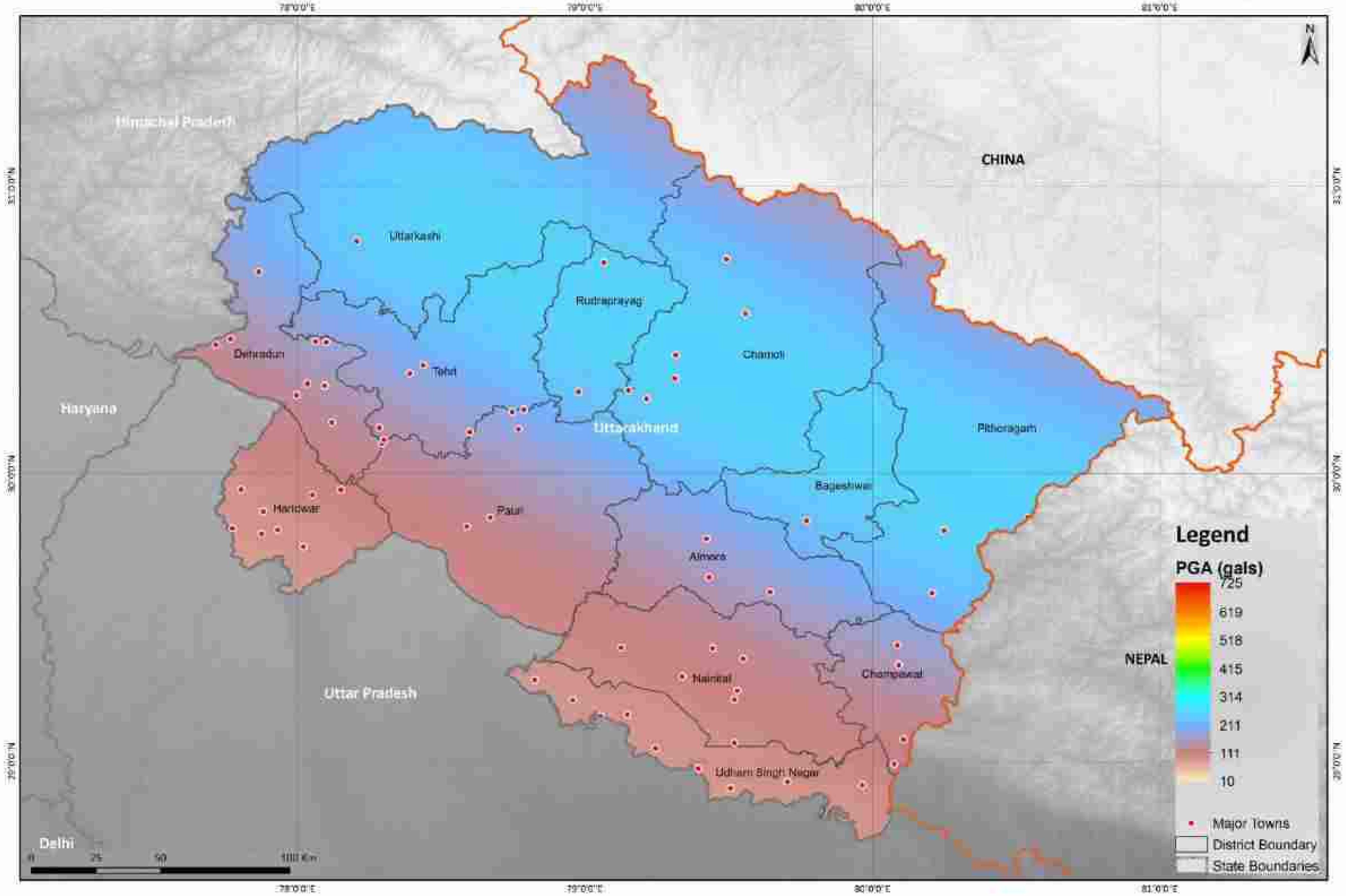

Figure 3.25: Seismic hazard map showing estimated PGA values (cm/s^2) in Uttarakhand with a 100 year return period

3.3.4 Seismic hazard map: 475 year return period

Seismic hazard intensities with a 475 year return period are mapped for Uttarakhand in Figure 3.26, showing a Peak Ground Acceleration ranging between 190.6 - 530.8 cm/s^2.

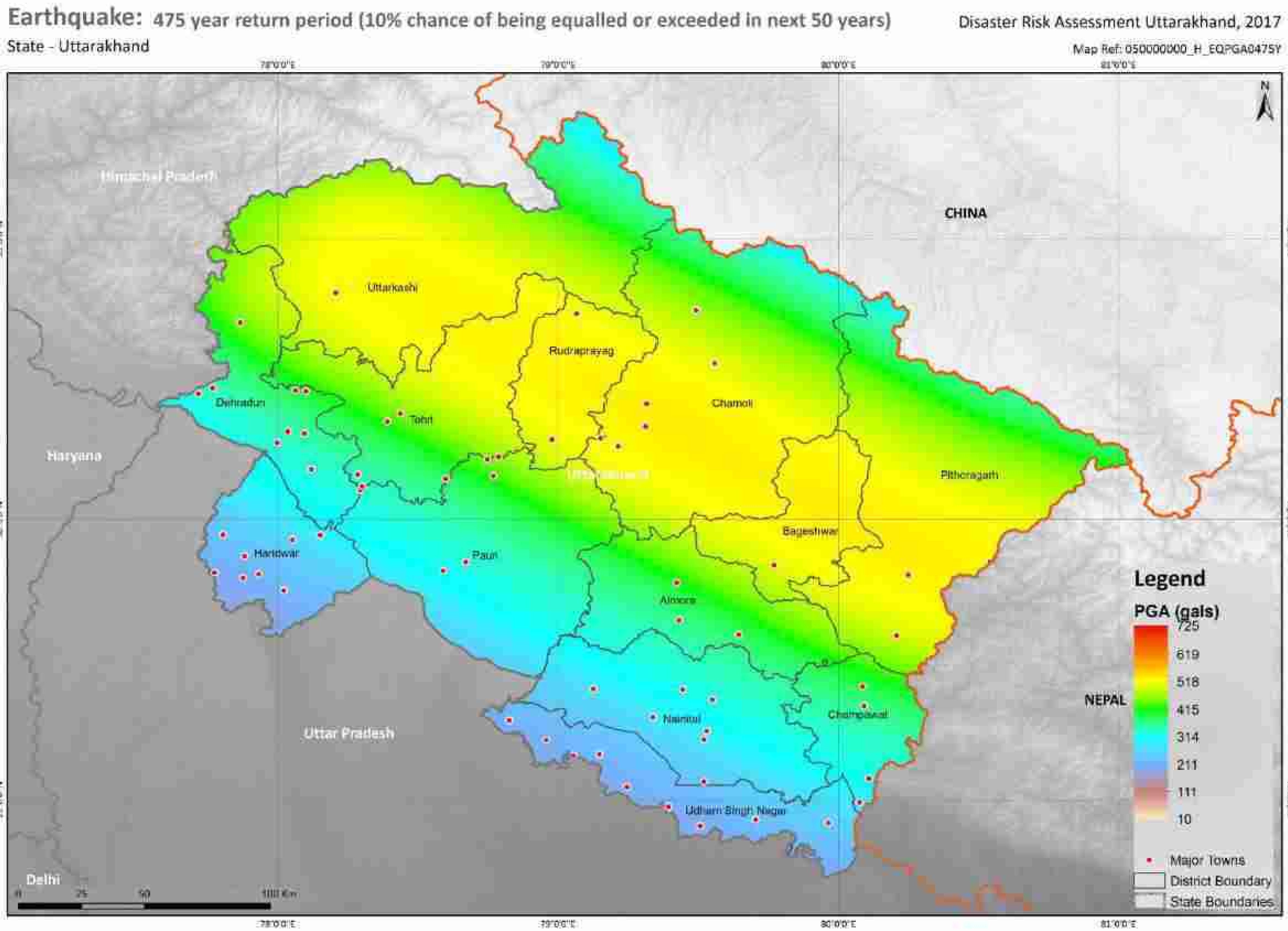

Figure 3.26: Seismic hazard map showing estimated PGA values (cm/s^2) in Uttarakhand with a 475 year return period

3.3.5 Seismic hazard map: 1,000 year return period

Seismic hazard intensities with a 1,000 year return period are mapped for Uttarakhand in Figure 3.27, showing a Peak Ground Acceleration ranging between 302.5 - 726.1 cm/s^2.

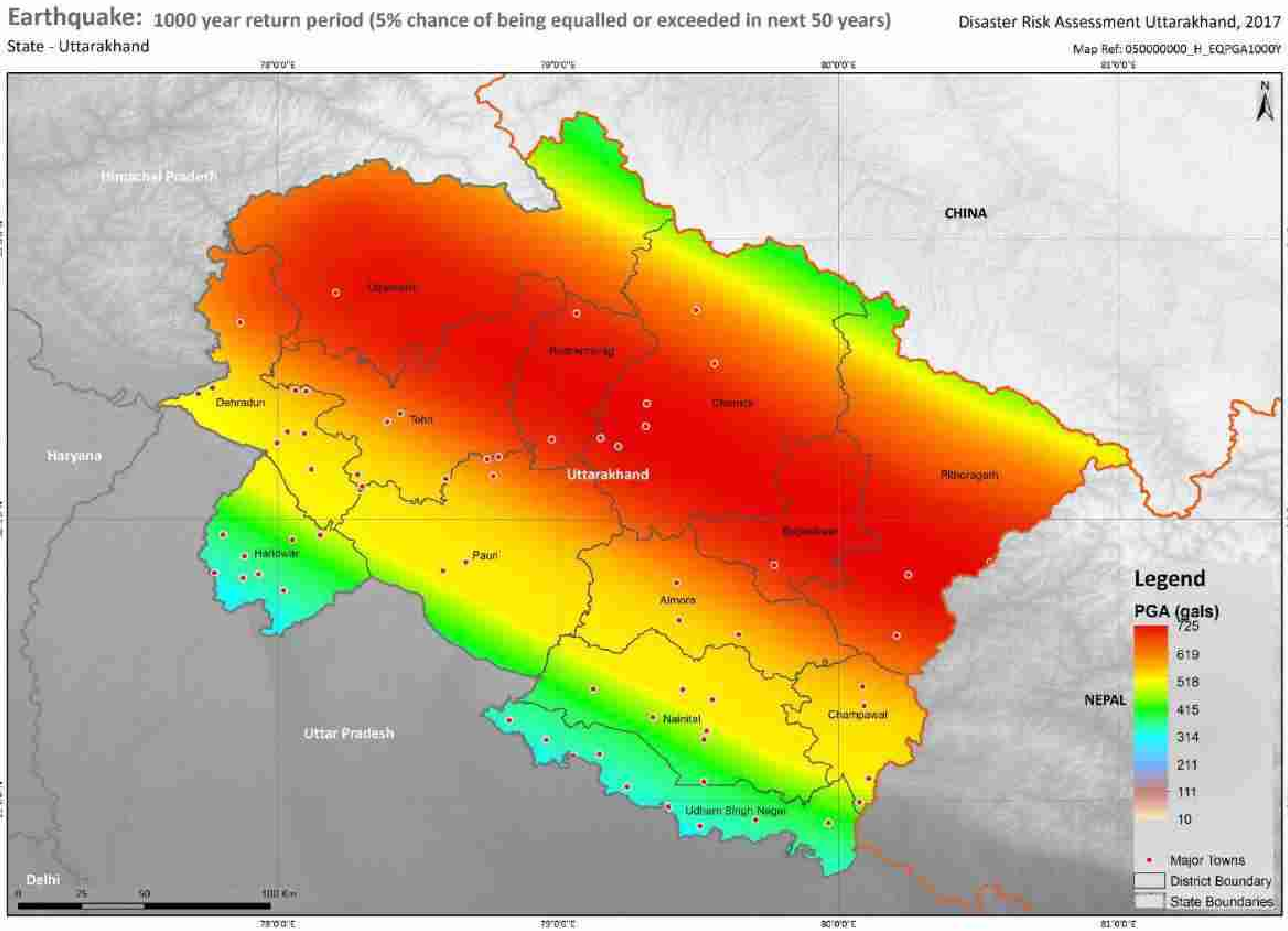

Figure 3.27: Seismic hazard map showing estimated PGA values (cm/s^2) in Uttarakhand with a 1,000 year return period

State

3.3 Earthquakes

Exposure Profile

This section presents a summary of the state's exposure to seismic hazards. Rather than estimating losses, the exposure assessment only looks at the extent to which people and economic assets are exposed to different hazard intensities, providing a useful preliminary indication of impact (which isn't subject to the uncertainties associated with economic valuation and vulnerability functions).

For this purpose, estimated PGA values for the 100 year return period earthquake hazard map were classified into felt intensity classes, using a conversion to the Modified Mercalli Intensity (MMI) classes previously proposed for the Indian context.[1] These intensity classes are based on observed effects, with lower classes defined by how earthquakes are felt by people and higher classes by observed structural damage, and provide an intuitive way to describe seismic intensity.

As shown in Table 3.2, the earthquake hazard intensities estimated across the state with a 100 year return period cover three MMI classes: Moderate, Strong and Very Strong. In order to be able to visualise and assess exposure in more detail, each of these classes has been split into five equally-spaced subclasses (such that the Moderate class is made up of subclasses M1 - M5, and so on). As can be seen from the table, the felt intensity of the 100 year return period hazard across the state ranges from a low of M5 (the highest Moderate subclass) up to a high of VS3 (the middle Very Strong subclass). All subsequent maps and plots illustrating exposure to hazards will use this classification system.

Table 3.2: Summary of MMI classification used for assessing the state's exposure to the 100 year RP earthquake hazard

MMI Class	PGA Range	Description	Subclass	100y RP
Moderate	24.0 - 46.7 cm/s²	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.	M1	
			M2	
			M3	
			M4	
			M5	
Strong	46.7 - 90.6 cm/s²	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.	S1	
			S2	
			S3	
			S4	
			S5	
Very Strong	90.6 - 176.0 cm/s²	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.	VS1	
			VS2	
			VS3	
			VS4	
			VS5	

[1] Ramalingeswara Roa, Prakasa Rao, T.K.S. and P. Sitapathi Rao. 1982. *A relationship of intensity, epicentral distance, focal depth, magnitude and acceleration*. Geophysical Research Bulletin **20**: 191–204.

Figure 3.28 visualises the exposure of all portfolios considered, in terms of the percentages of each population group or economic asset exposed to "limited" (Moderate/Strong) as opposed to "significant" (Very Strong) earthquake intensities (with reference to the 100 year return period earthquake intensities). In the sections which follow, each portfolio will be considered separately, showing the felt intensities to which they are each likely to be exposed (in each case based on the 100 year return period intensities).

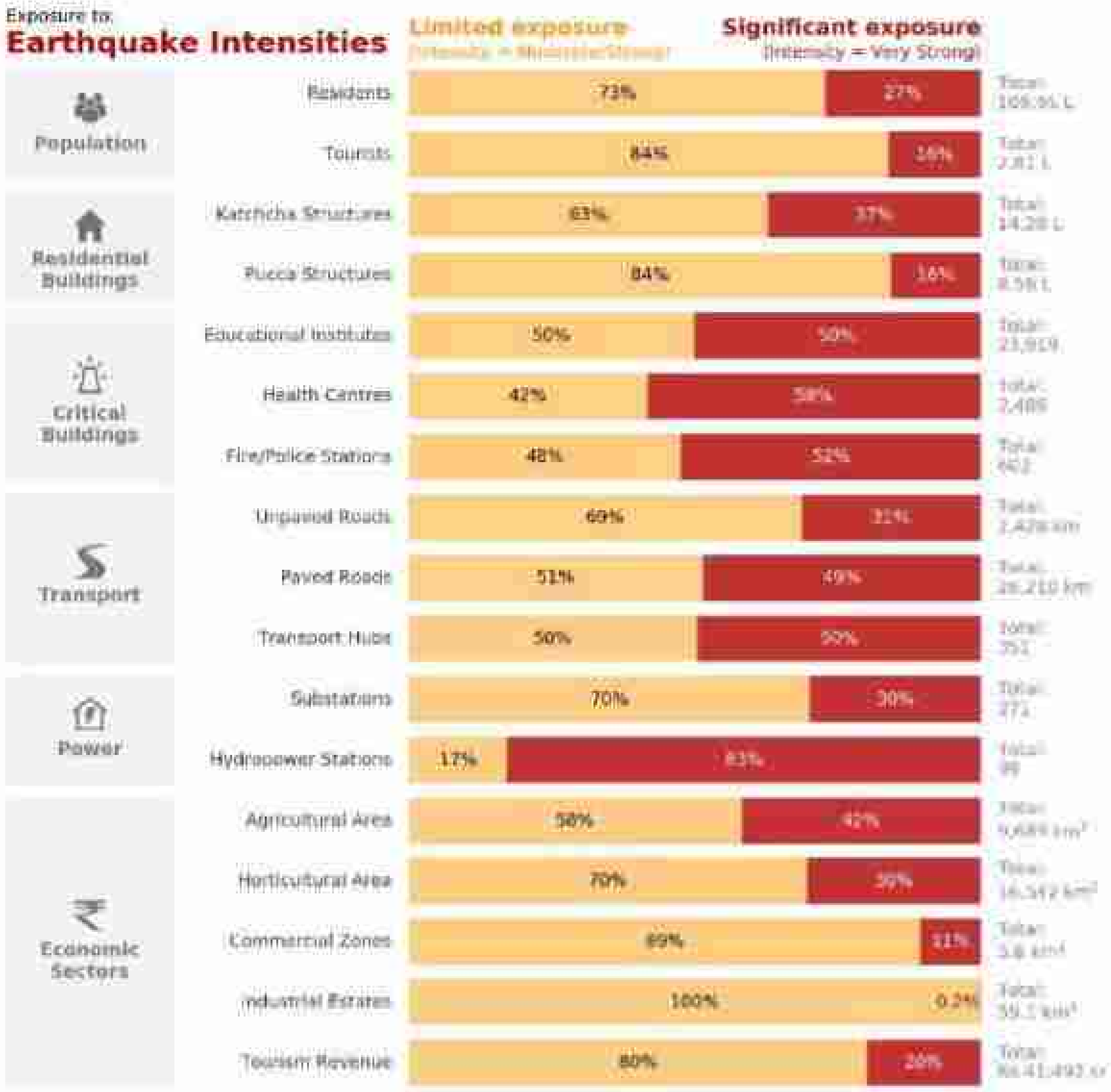

Figure 3.28: Visual summary of the State's overall exposure to earthquake intensities with a 100 year return period

3.3.6 Population exposure to earthquakes

Figure 3.29 shows the exposure of the resident population to earthquake intensities with a return period of 100 years. Note that a comparison of day-time versus night-time exposure is made, based on assumptions regarding the spatial distribution of the population at different times (with more people likely to be indoors at night and thus vulnerable to earthquakes). For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

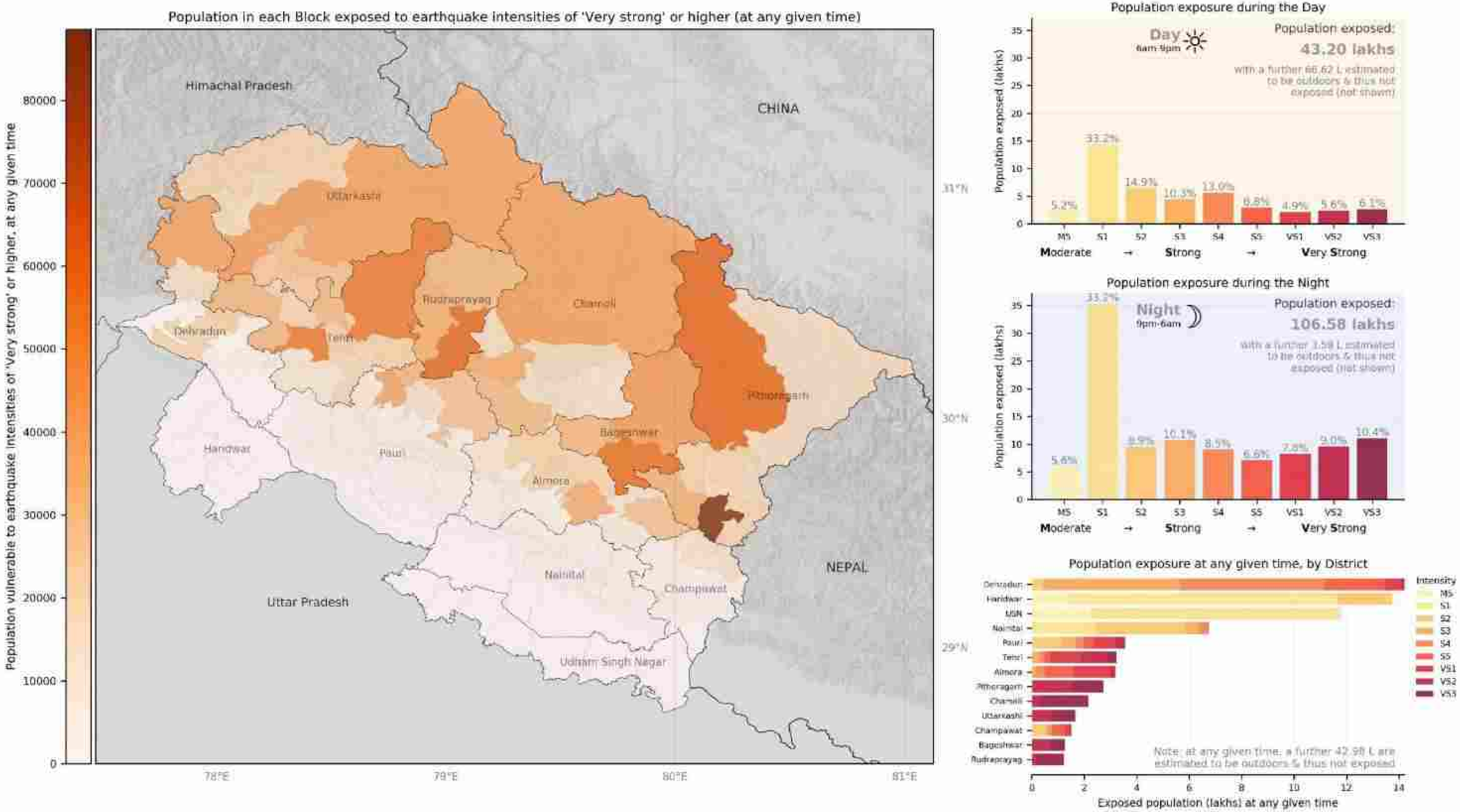

Figure 3.29: Visual summary of the resident population exposed to earthquake intensities with a 100 year return period

Figure 3.30 shows the exposure of tourists to earthquake intensities with a return period of 100 years. As for residents, a comparison of day-time versus night-time tourist exposure is made, based on assumptions regarding the spatial distribution of the population at different times (with more people likely to be indoors at night and thus vulnerable to earthquakes). (Note also that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values). For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

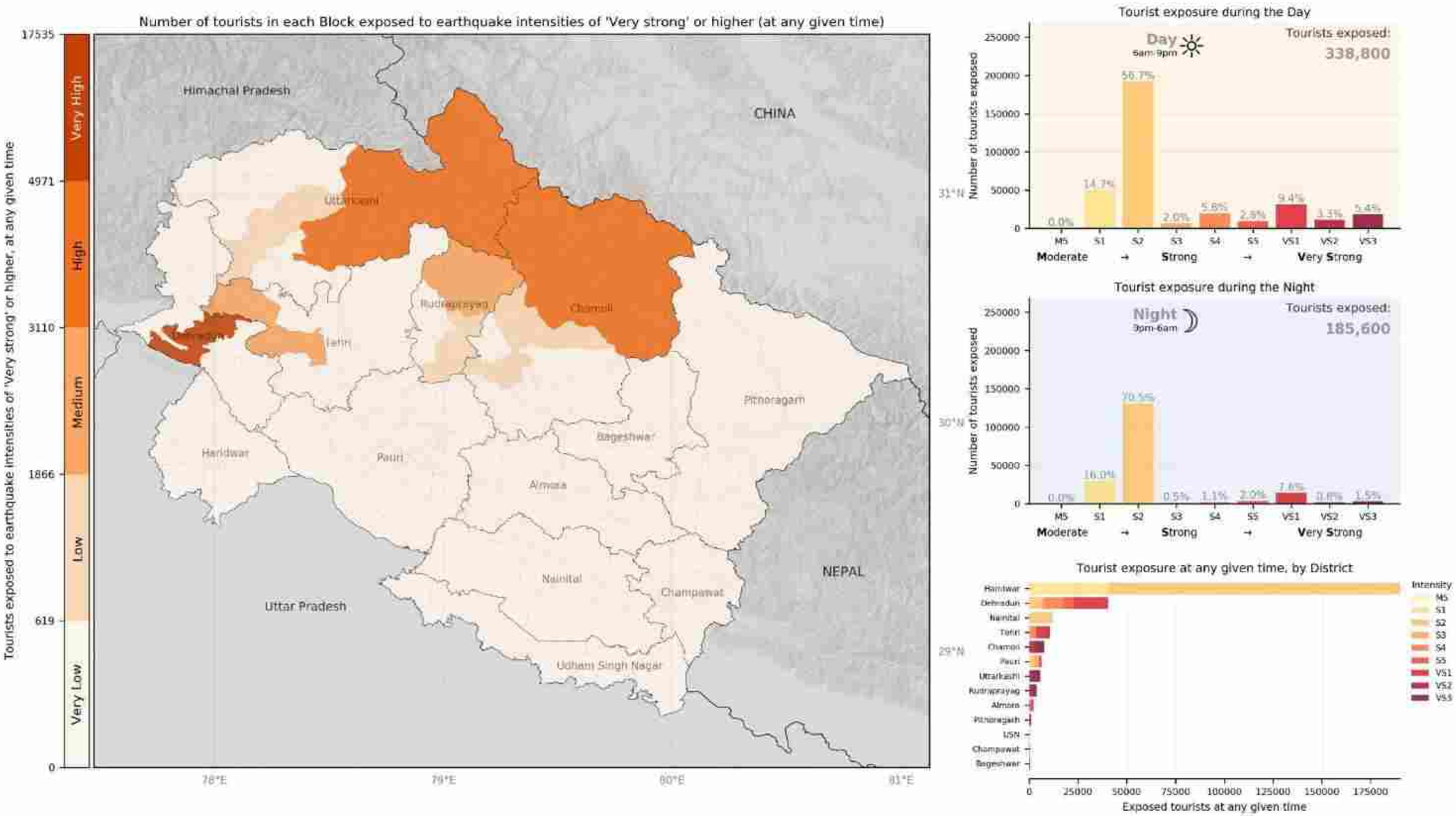

Figure 3.30: Visual summary of tourist population exposed to earthquake intensities with a 100 year return period

3.3.7 Residential building exposure to earthquakes

Figure 3.31 shows the exposure of residential buildings to earthquake intensities with a return period of 100 years. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

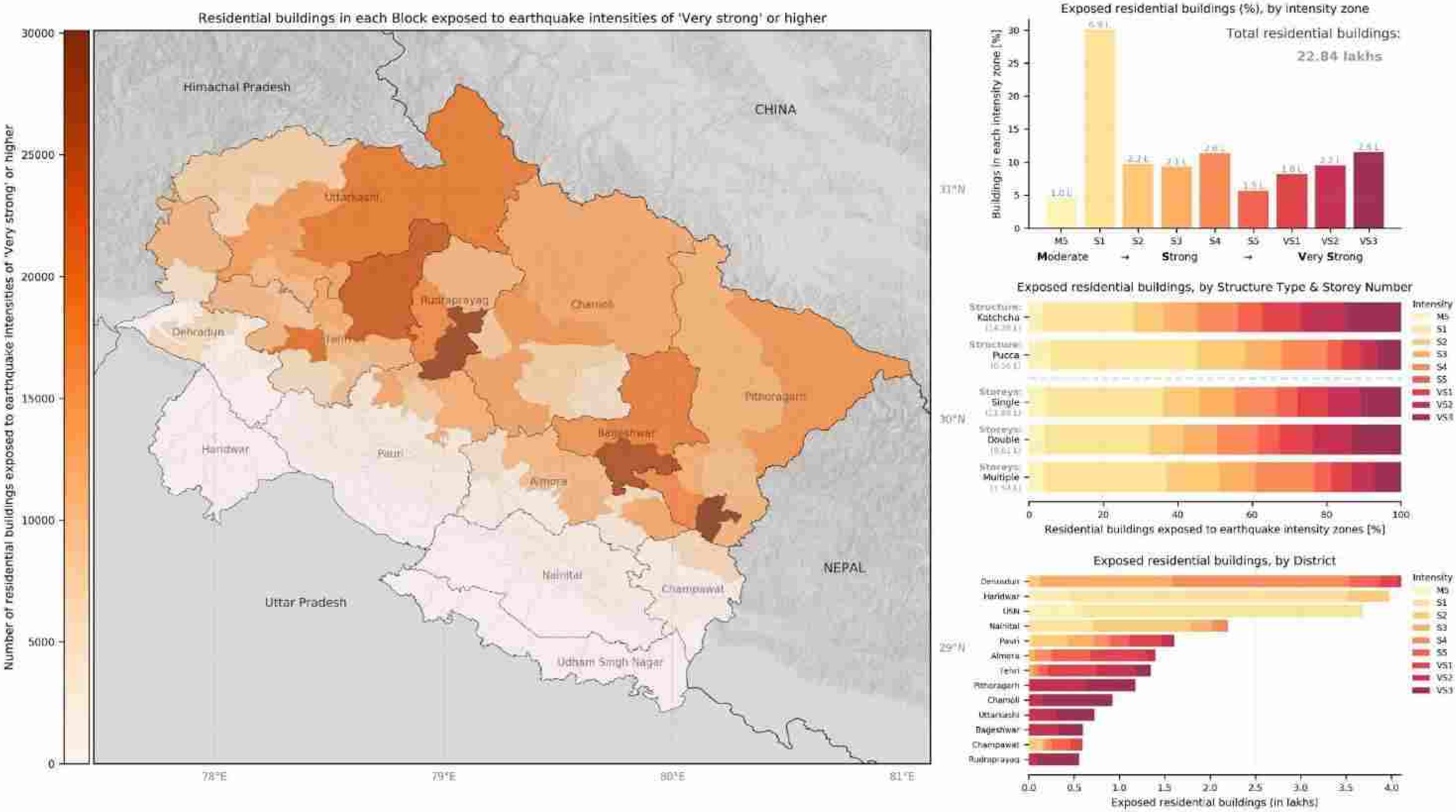

Figure 3.31: Visual summary of residential buildings exposed to earthquake intensities with a 100 year return period

3.3.8 Critical building exposure to earthquakes

Figure 3.32 shows the exposure of critical buildings to earthquake intensities with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of health facilities, educational institutions, fire/police stations and other government buildings. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

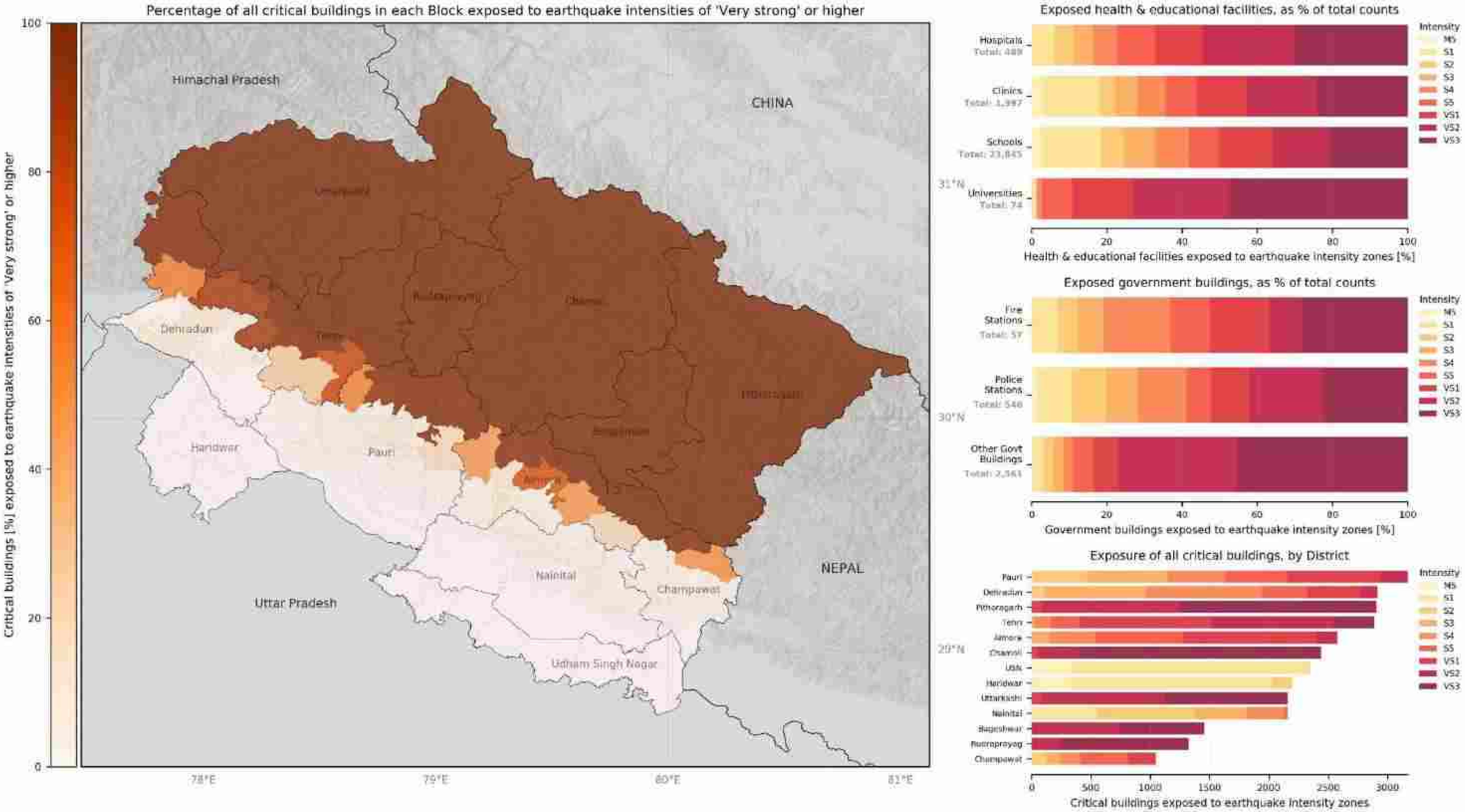

Figure 3.32: Visual summary of critical buildings exposed to earthquake intensities with a 100 year return period

3.3.9 Transportation infrastructure exposure to earthquakes

Figure 3.33 shows the exposure of transportation infrastructure to earthquake intensities with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of road, rail and air infrastructure. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

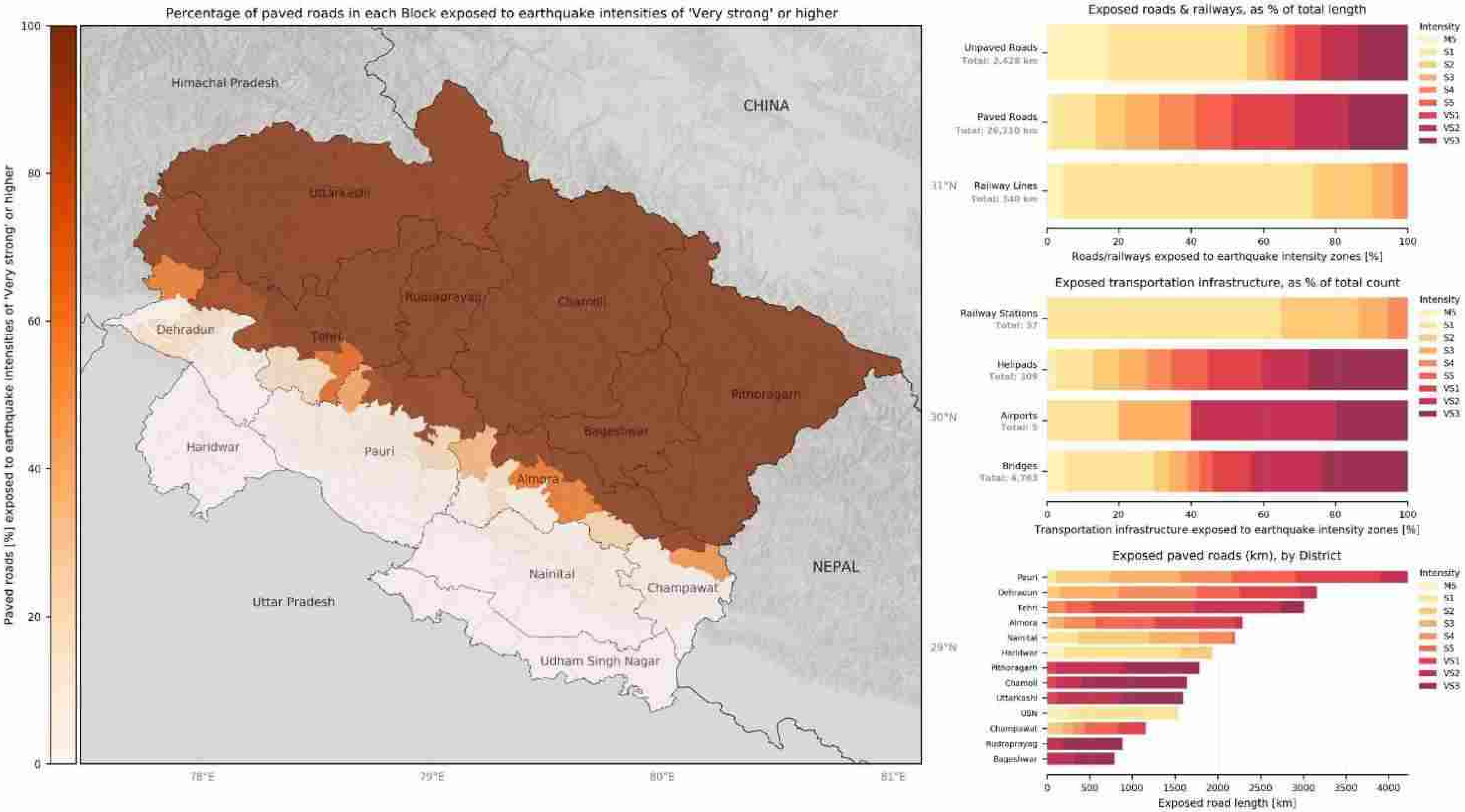

Figure 3.33: Visual summary of transport infrastructure exposed to earthquake intensities with a 100 year return period

3.3.10 Power infrastructure exposure to earthquakes

Figure 3.34 shows the exposure of power infrastructure to earthquake intensities with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of substations (transmission and distribution), hydropower stations and dams. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

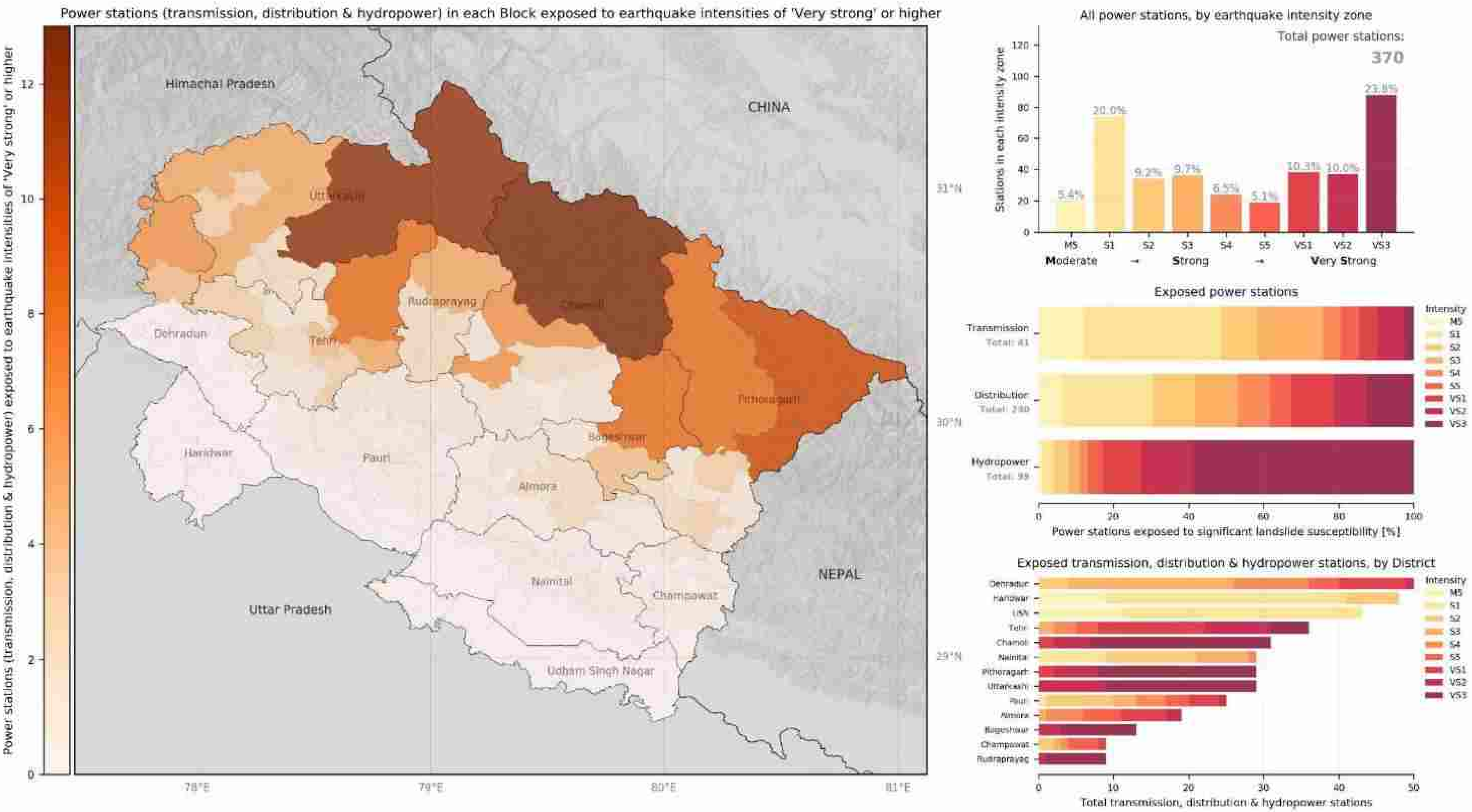

Figure 3.34: Visual summary of power infrastructure exposed to earthquake intensities with a 100 year return period

3.3.11 Economic sector exposure to earthquakes

Figure 3.35 shows the exposure of agriculture (which includes equipment and other forms of capital investment) to earthquake intensities with a return period of 100 years. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

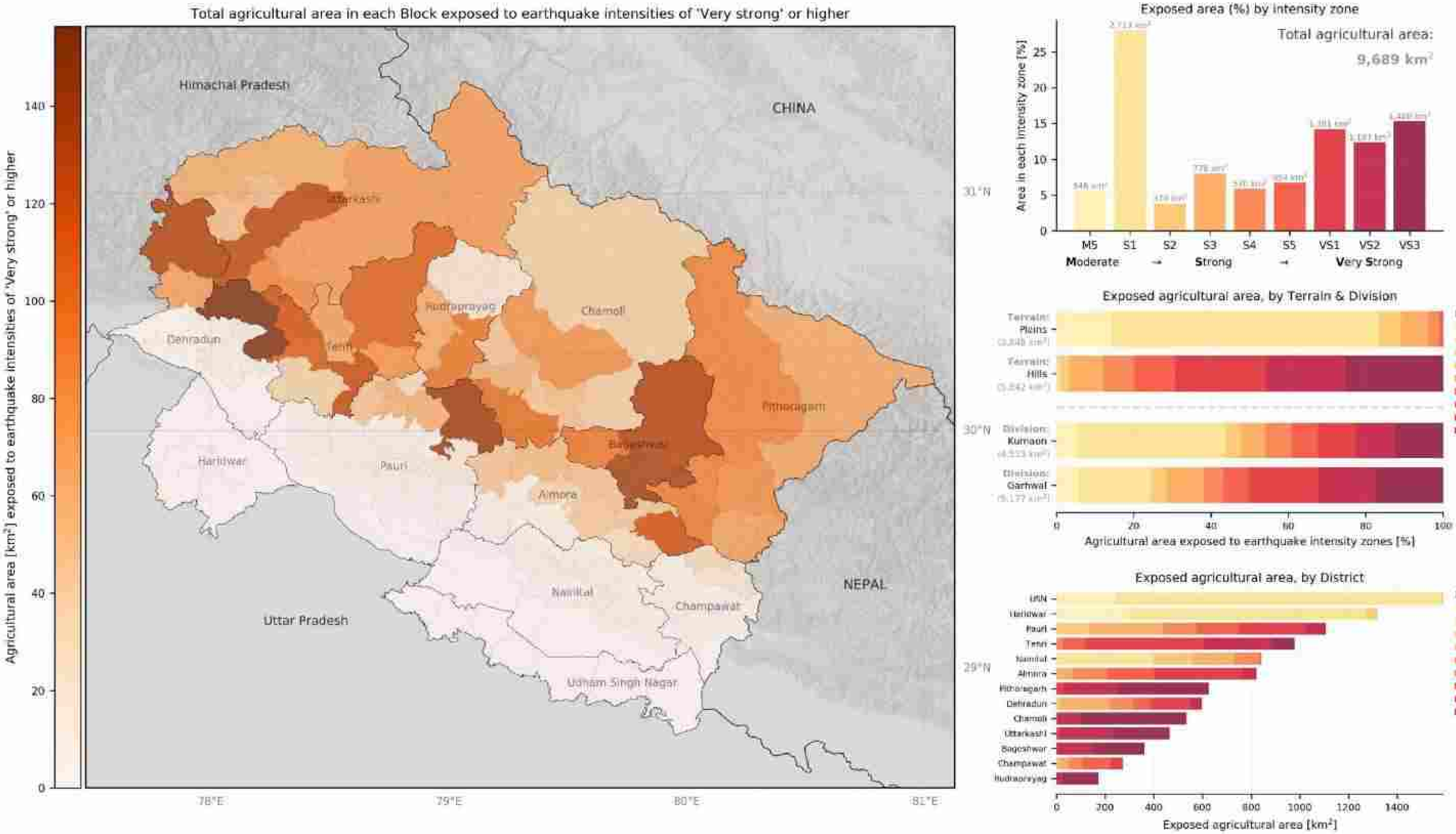

Figure 3.35: Visual summary of agriculture exposed to earthquake intensities with a 100 year return period

Figure 3.36 shows the exposure of horticulture (which includes equipment and other forms of capital investment) to earthquake intensities with a return period of 100 years. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

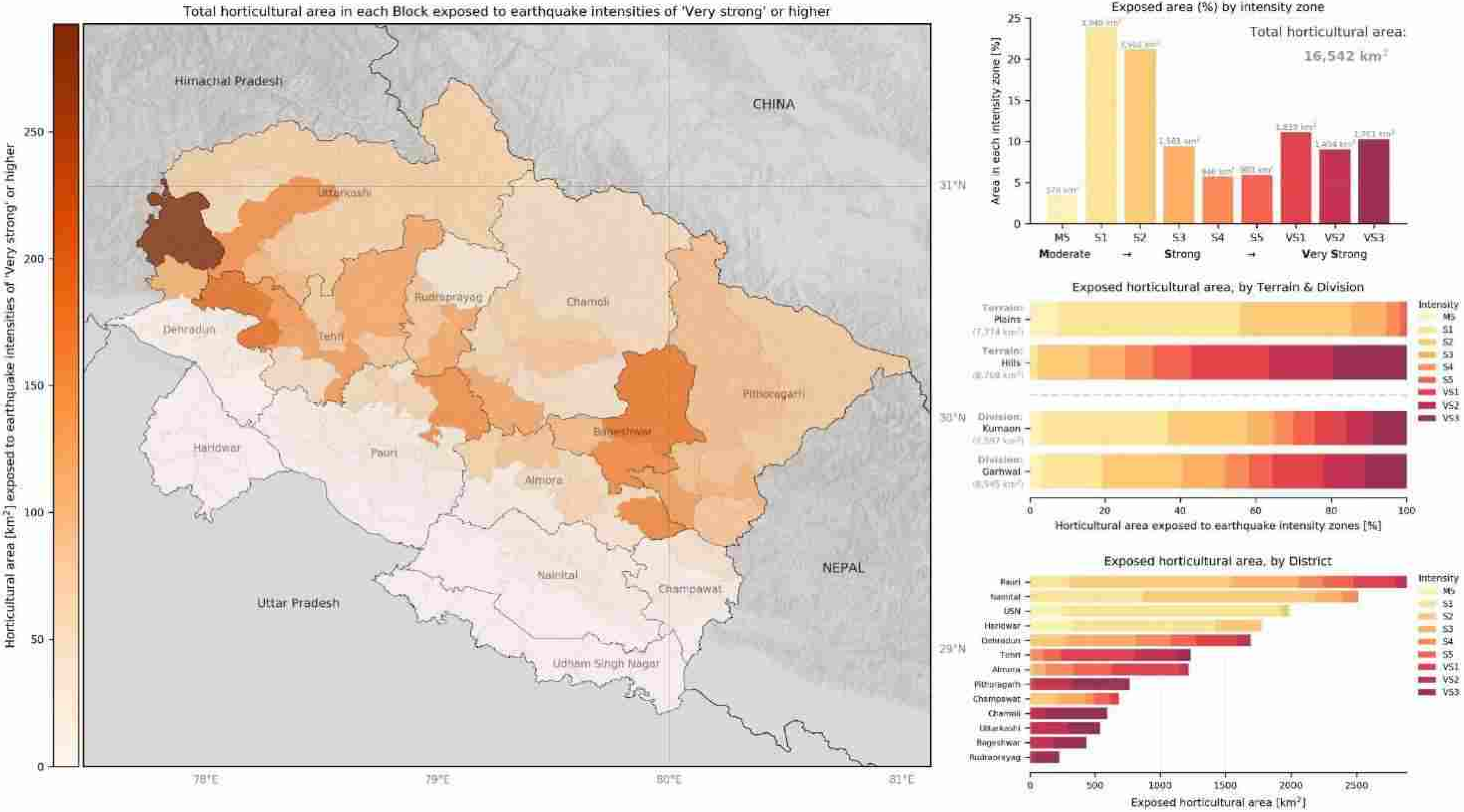

Figure 3.36: Visual summary of horticulture exposed to earthquake intensities with a 100 year return period

Figure 3.37 shows the exposure of industry, commerce and mining to earthquake intensities with a return period of 100 years. For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

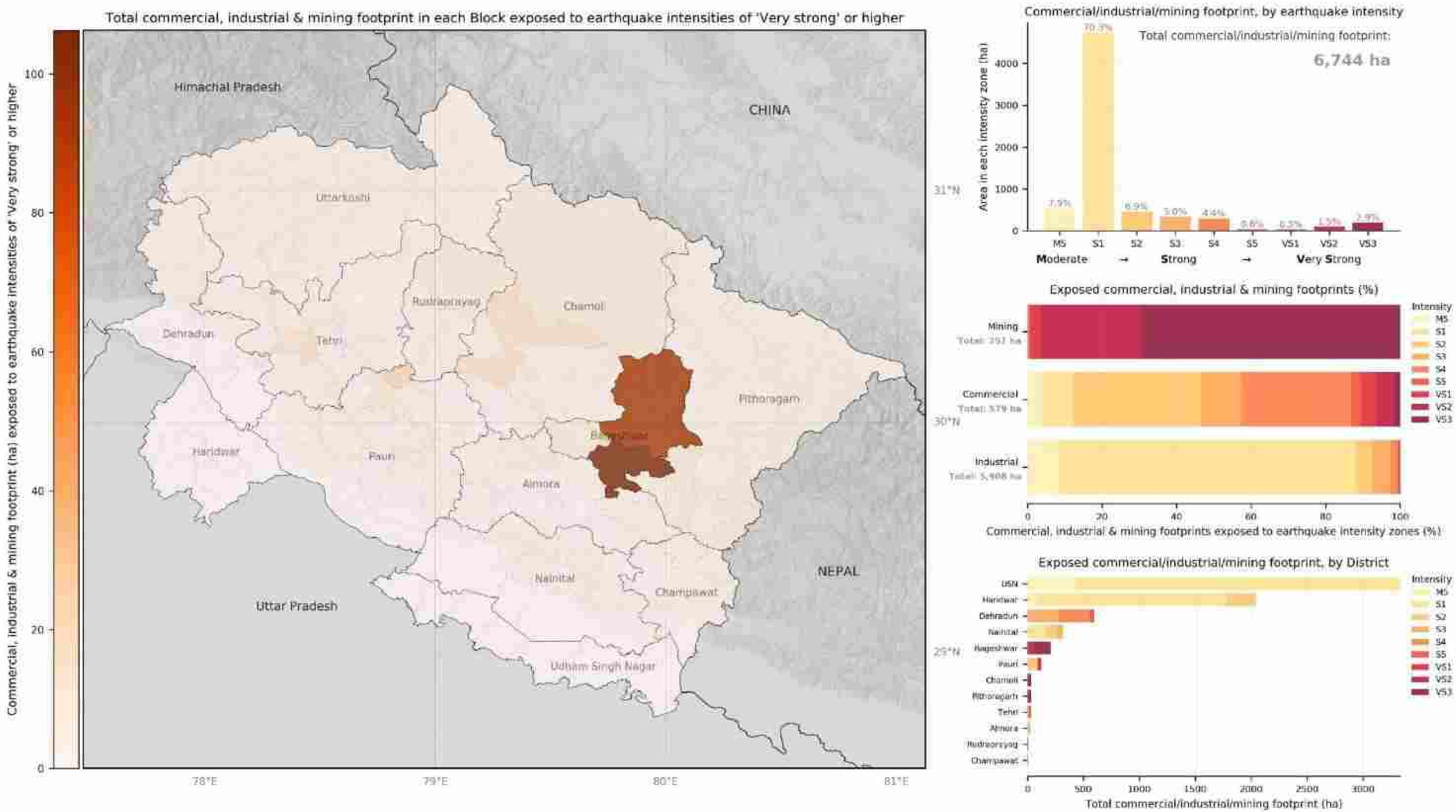

Figure 3.37: Visual summary of industry, commerce and mining exposed to earthquake intensities with a 100 year return period

Figure 3.38 shows the exposure of potential tourism revenue to earthquake intensities with a return period of 100 years. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values). For an explanation of the intensity classes used, the reader is referred to Table 3.2 (at the beginning of the Exposure Profile section).

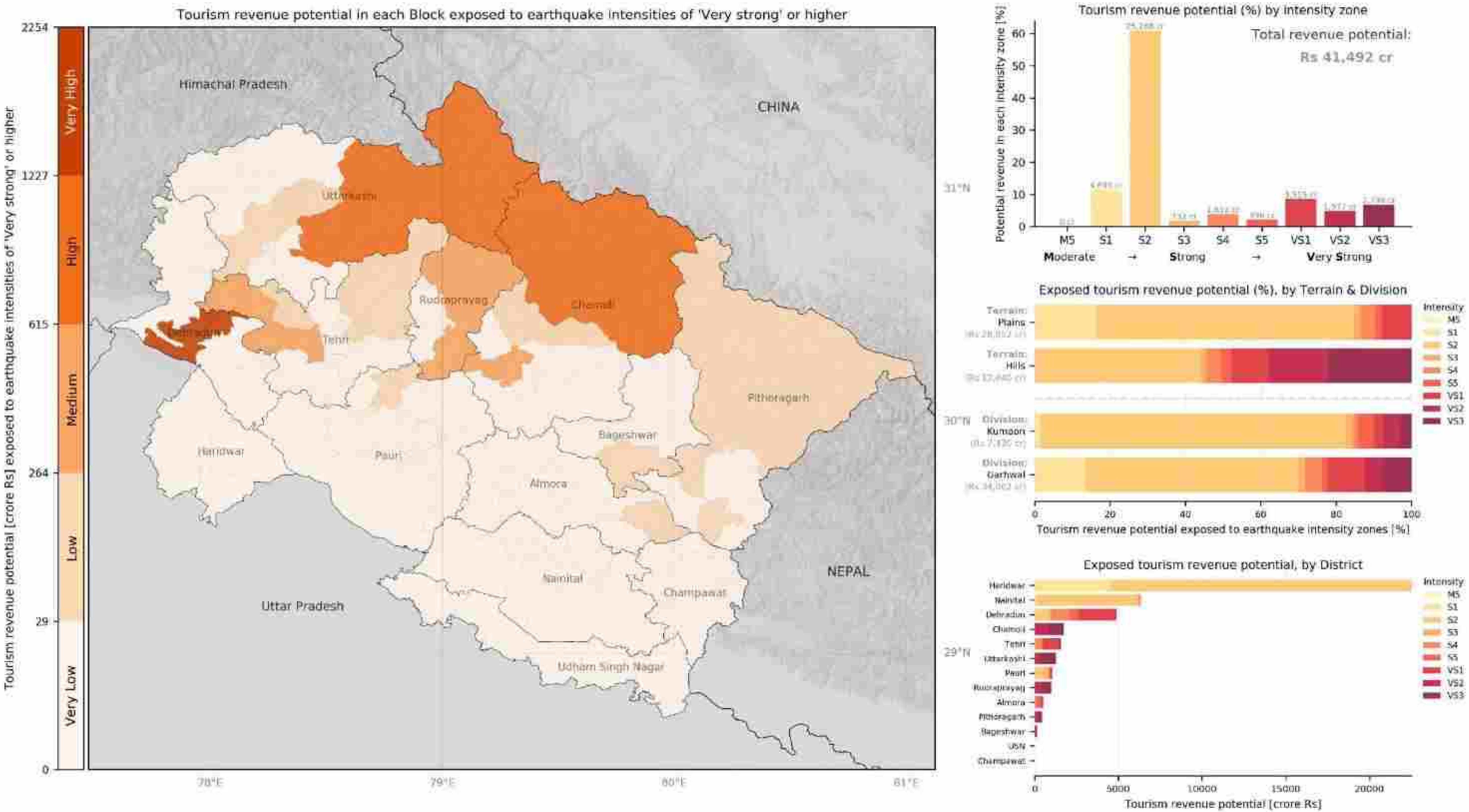

Figure 3.38: Visual summary of tourism revenue potential exposed to earthquake intensities with a 100 year return period

3.3 Earthquakes

/ Loss Profile

The Average Annual Loss (AAL) of economic value in the State due to earthquakes is approximately Rs 2,480 crores. Figure 3.39 shows how this total is distributed between the various portfolios and their individual components.

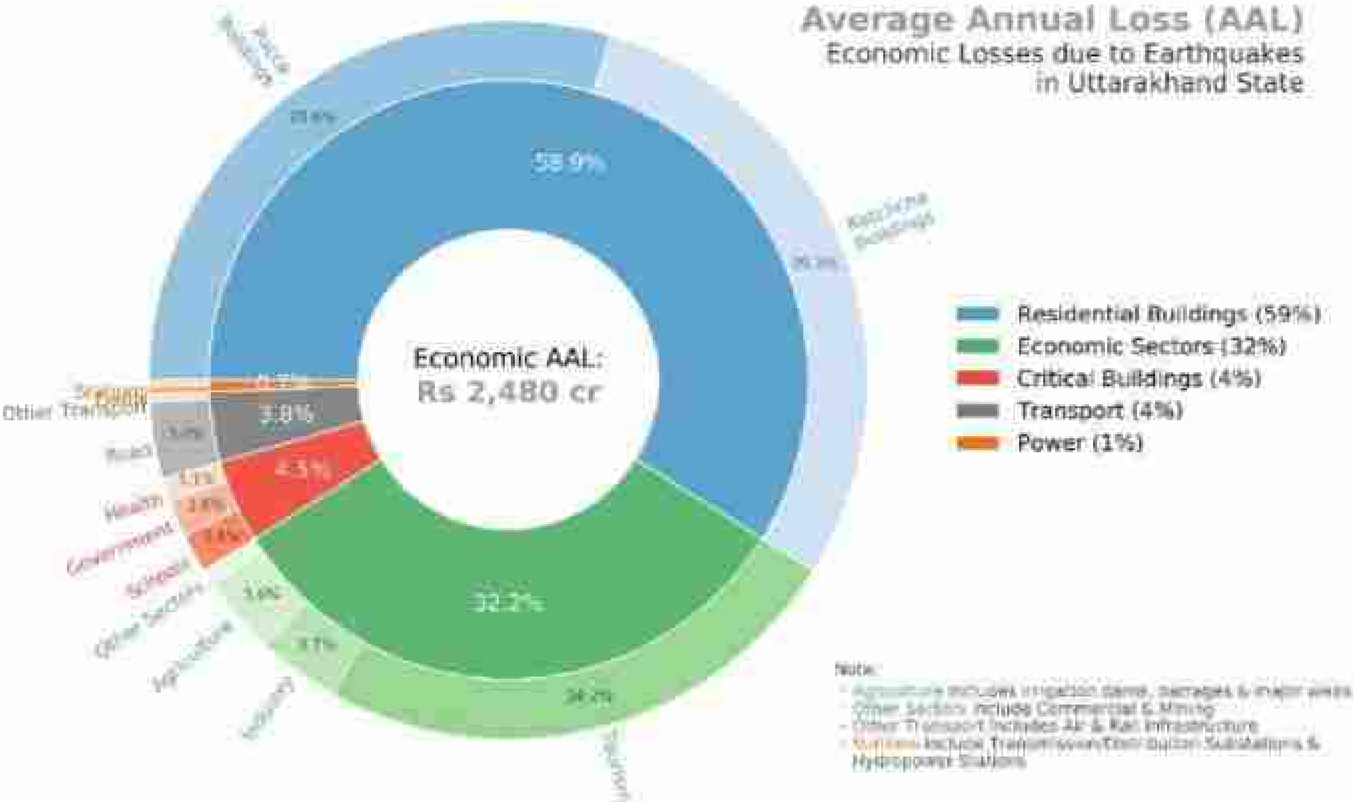

Figure 3.39: Distribution of Economic AAL due to earthquakes, by portfolio and sub-portfolio

In Figure 3.40, the total AAL of economic value in each district is displayed, as well as the distribution of each district's total AAL by portfolio.

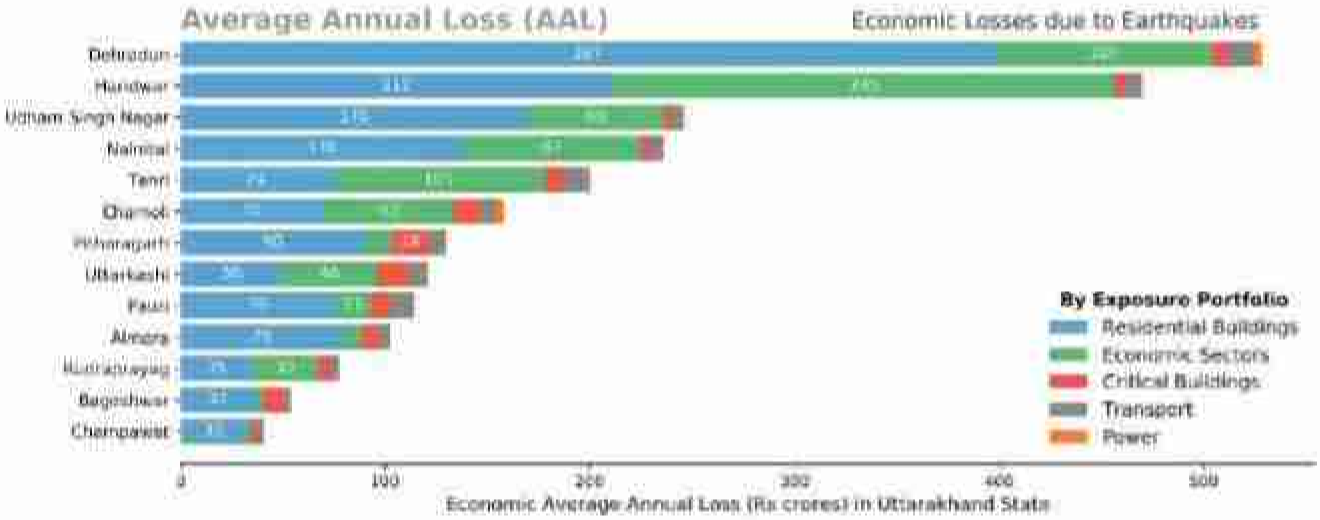

Figure 3.40: Distribution of Economic AAL due to earthquakes, by portfolio and district

The economic losses presented above include both direct losses (those incurred at the time of the disaster, in terms of damaged assets that have to be repaired or replaced) and indirect losses (the loss of likely future income due to the disruption of revenue streams such as industrial production or tourism activities).

In the case of the latter, assumptions must be made as to the maximum period over which revenue streams may be impacted by a given disaster (with actual losses scaled proportionately according to the calculated damage percentage). Table 3.3 summarises these assumptions for each economic portfolio/sub-portfolio included in the risk assessment, as well as providing a general overview of the direct and indirect losses considered. It is noted that cascading indirect losses (such as industrial losses due to disruption of power infrastructure) are not within the scope of the current assessment and therefore not accounted for in the loss estimates.

Table 3.3: Overview of direct and indirect losses accounted for, including maximum disruption periods for indirect losses

Portfolio	Sub-portfolios	Direct losses	Indirect losses	Max disruption
Residential Buildings	Katchcha	Replacement cost	None	NA
	Pucca			
Critical Buildings	Health, Schools, Government	Replacement cost	None	NA
Transport Infrastructure	Road, Rail, Air	Replacement cost	None	NA
Power Infrastructure	Power substations	Replacement cost	None	NA
	Hydropower stations	Replacement cost	Loss of electricity revenue	1 year
Economic Sectors	Agriculture, Horticulture	Replacement cost (capital investment)	Loss of future yields	1 year
	Industry	Replacement cost (capital investment)	Loss of future production revenue	1 year
	Commerce	None	Loss of manufacturing & services revenue	1 year
	Mining	None	Loss of production revenue	1 year
	Tourism	None	Loss of tourism revenue	3 years (remote) 2 years (moderate) 1 year (accessible)

Figure 3.41 illustrates the distribution of direct and indirect losses within the state's overall economic AAL due to earthquakes.

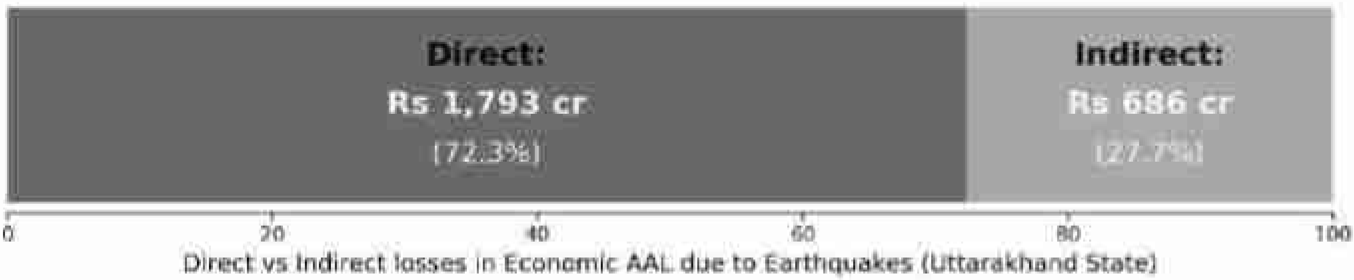

Figure 3.41: Distribution between direct and indirect losses in the state's Economic AAL, due to earthquakes

Figure 3.42 presents the ranking of all Districts and Blocks within the State, in terms of their total Average Annual Loss (AAL) of economic assets, as a result of both direct and indirect losses caused by earthquakes.

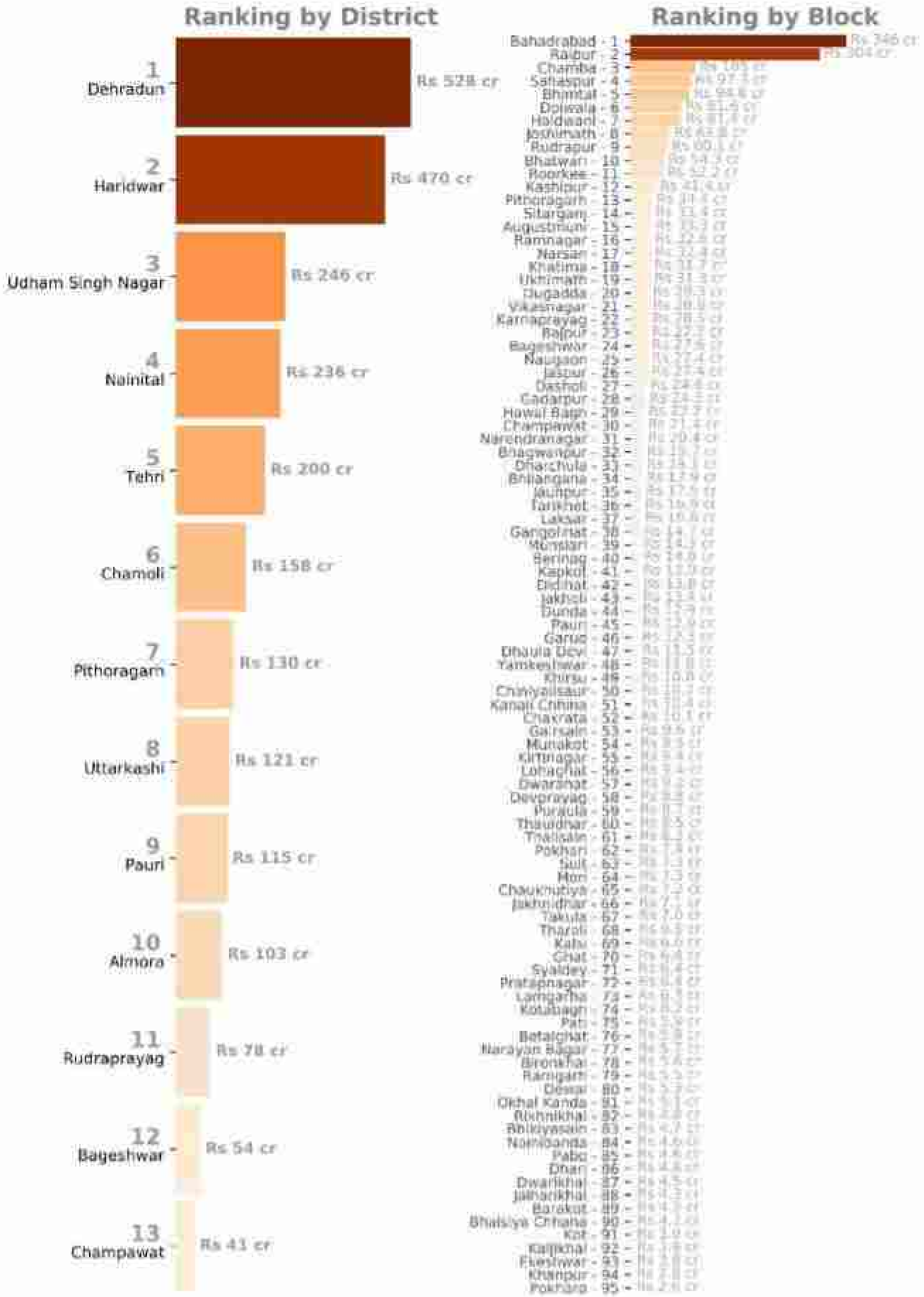

Figure 3.42: Ranking of all Districts and Blocks in the state, based on Average Annual Loss (Economic) due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.43 presents the overall PML curve for all economic assets modelled in the state.

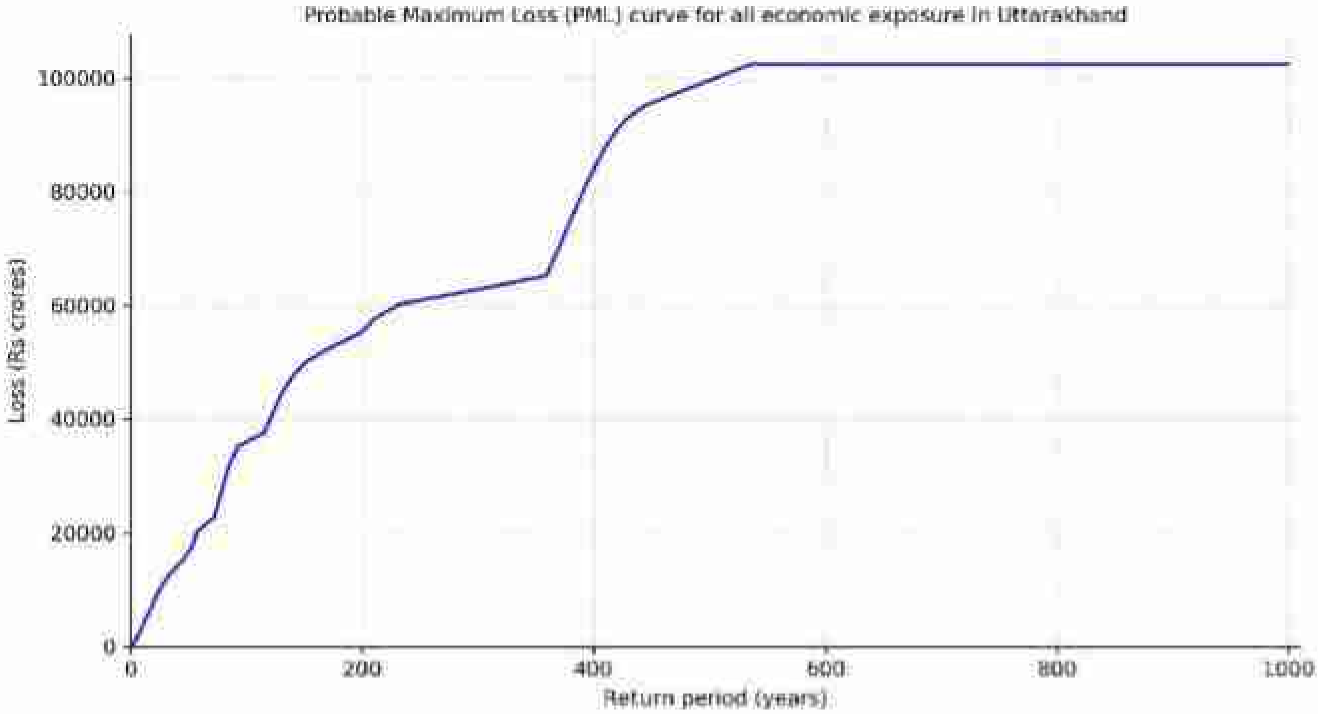

Figure 3.43: Probable Maximum Loss (PML) curve for all economic assets in Uttarakhand due to earthquakes

Figure 3.44 presents individual PML curves for each of the mapped economic portfolios in the state.

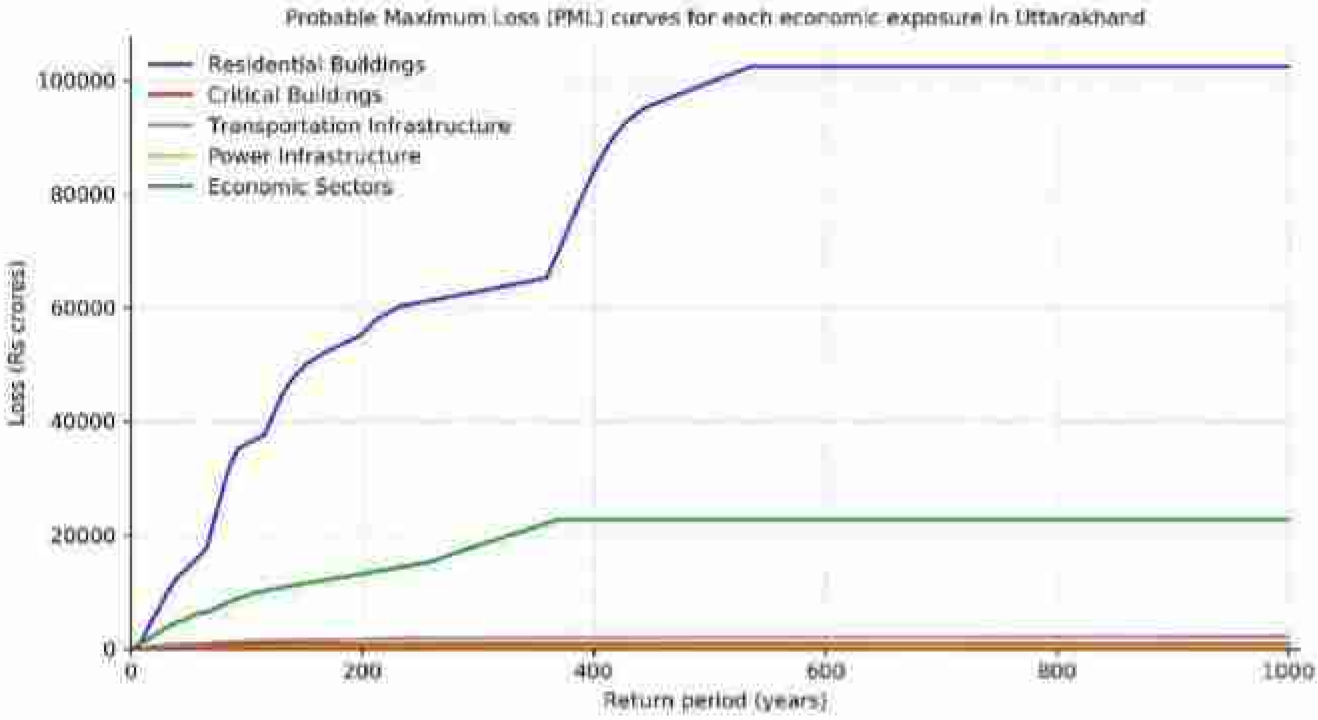

Figure 3.44: Probable Maximum Loss (PML) curves for each economic asset in Uttarakhand due to earthquakes

As for human losses, the Average Annual Loss (AAL) in the State due to earthquakes is estimated to be 3,500 lives. Figure 3.45 summarises the distribution of this total, in terms of the residency of those killed (state residents or tourists), the time of the earthquake (more people are inside buildings at night and therefore more exposed), and the structural quality of the building they were in at the time (in terms of Katchcha/Pucca structural types).

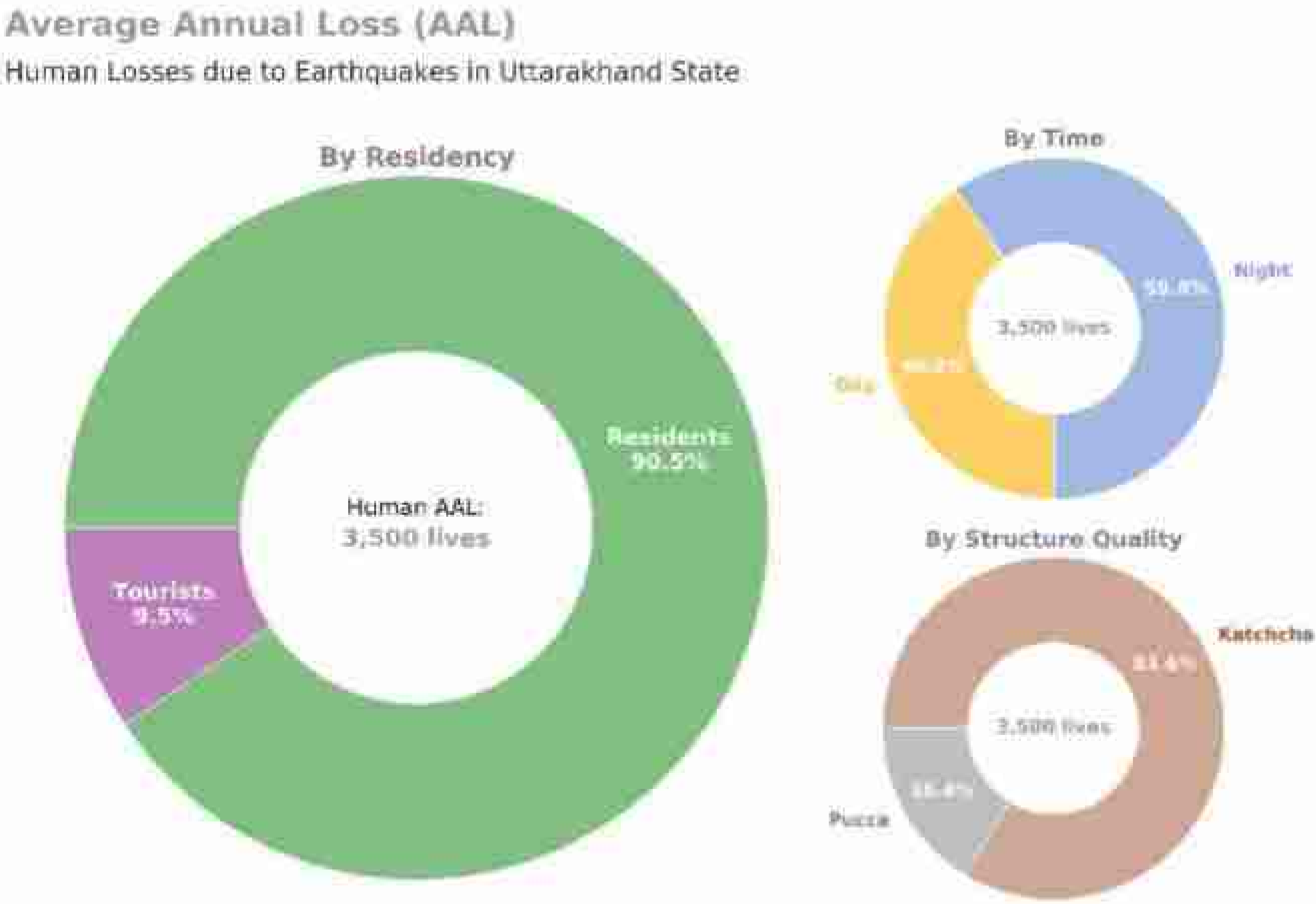

Figure 3.45: Average Annual Loss (AAL) of human lives, by residency, time of earthquake and building quality

Figure 3.46 summarises the AAL of human lives in each of the State's districts, as well as the distribution of each district's AAL in terms of the residency of those affected (state residents or tourists).

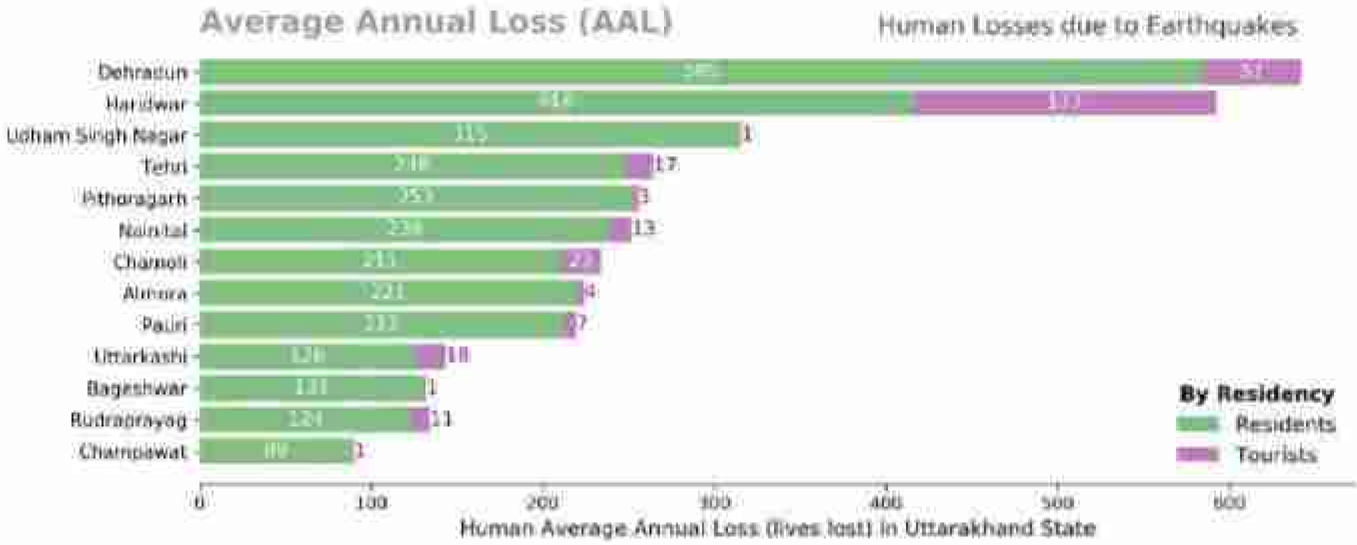

Figure 3.46: Average Annual Loss (AAL) of human lives, by district and residency (residents/tourists)

Figure 3.47 presents the ranking of all Districts and Blocks within the State, in terms of their total Average Annual Loss (AAL) of human life, as a result of earthquake hazards.

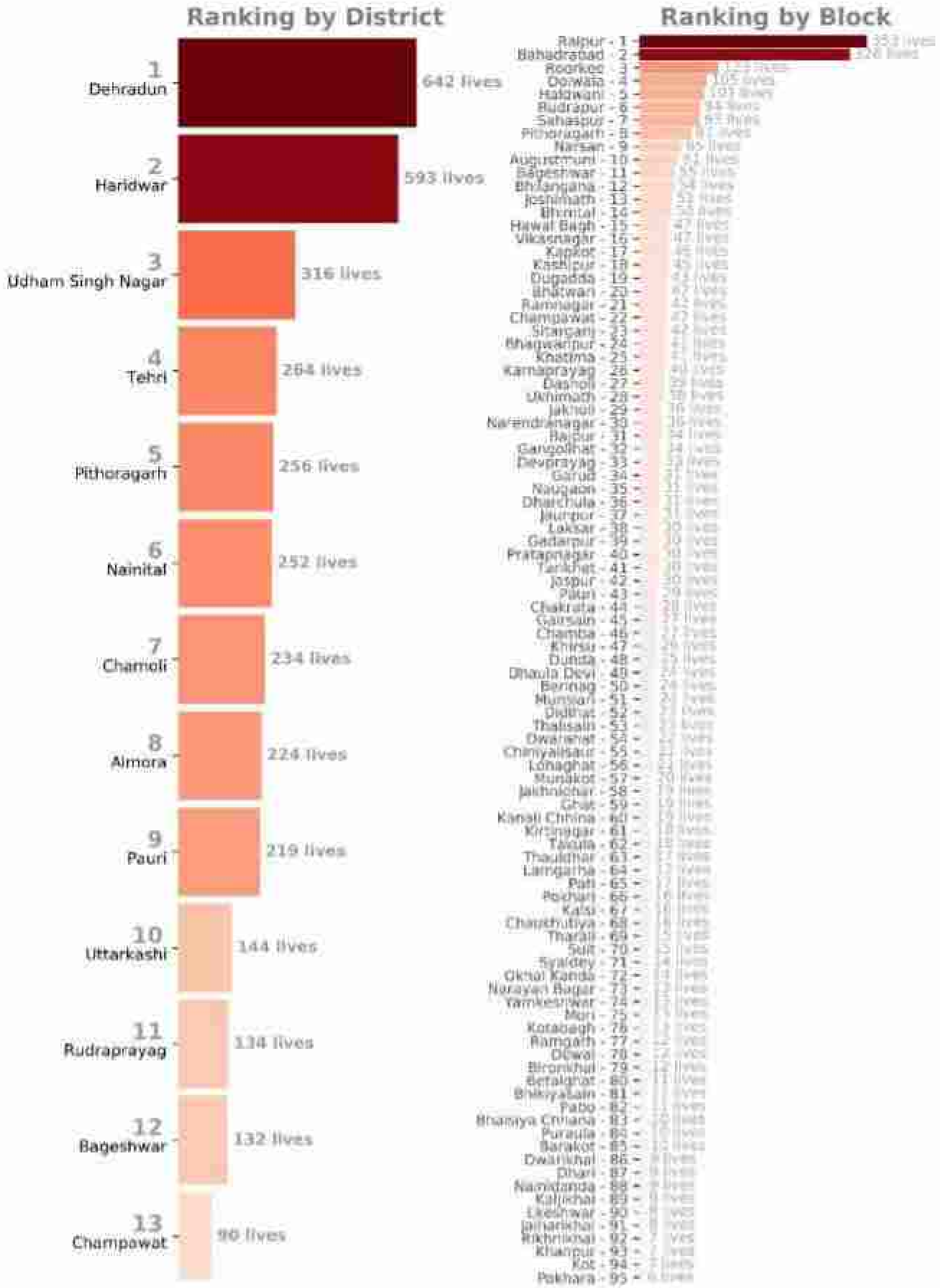

Figure 3.47: Ranking of all Districts and Blocks in the state, based on Average Annual Loss (Human) due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.48 presents the overall PML curve for all people (residents and tourists) in the state.

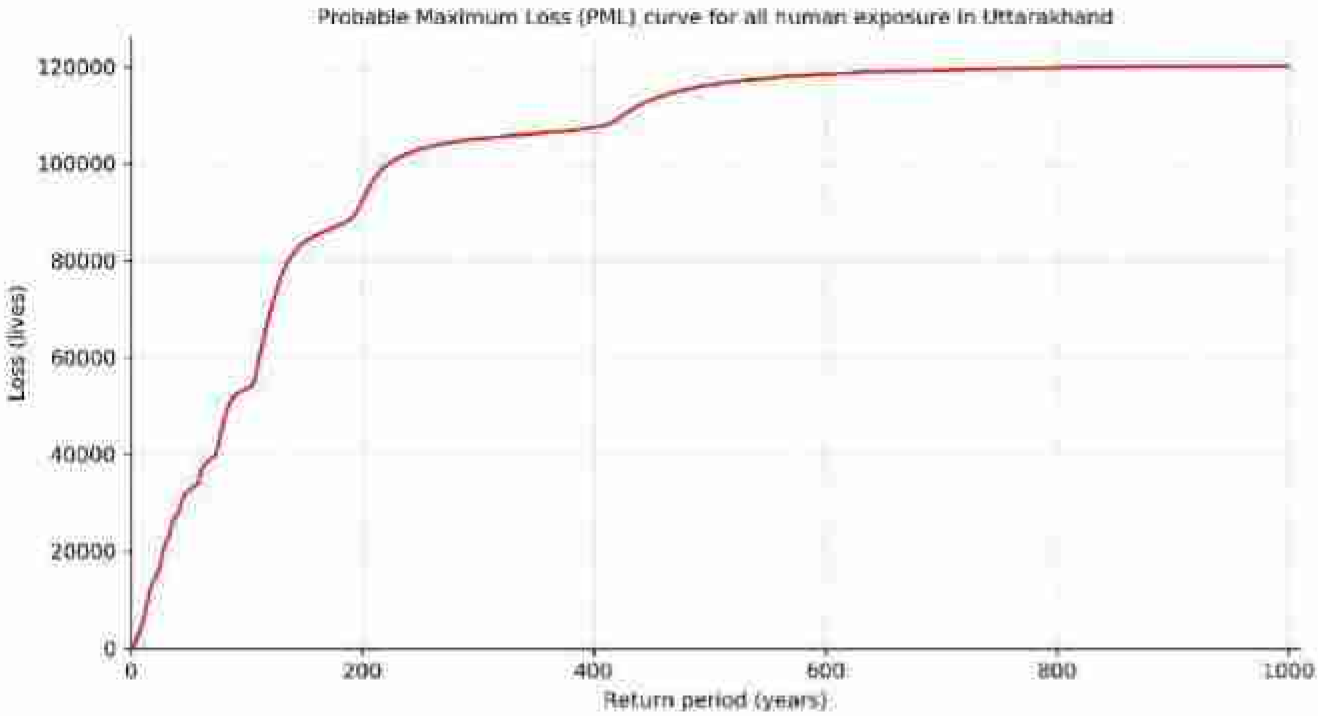

Figure 3.48: Probable Maximum Loss (PML) curve for all human populations in Uttarakhand due to earthquakes

Figure 3.49 presents individual PML curves exploring the impact of earthquake timing on likely fatalities, given very different spatial distributions of population at different times of day.

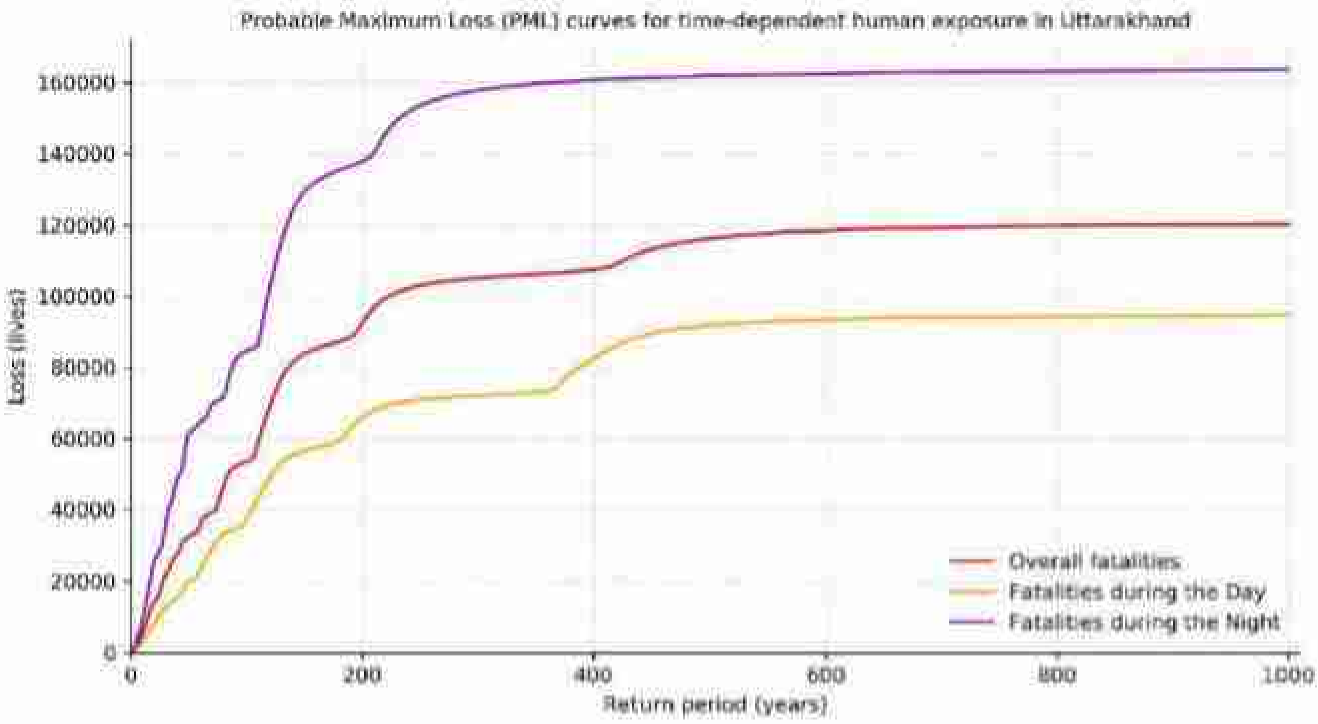

Figure 3.49: Probable Maximum Loss (PML) curve for all human populations in Uttarakhand due to earthquakes, at different times of day (based on modelled differences in the spatial distribution of the exposed population)

The human AAL discussed so far provides an estimate of the likely loss of life directly attributable to earthquakes (primarily resulting from the collapse of buildings during or immediately following the earthquake). However, there are likely to be longer-term morbidity impacts too, depending on the extent to which the affected area's capacity to respond to the disaster has been compromised. This will depend on factors such as:

- Size of displaced population to be housed in temporary camps (where disease outbreaks more likely)
- Capacity of local health facilities (those still functional post-disaster)
- Capacity of other government facilities to support response/recovery efforts
- Transport connectivity within the affected area (particularly road and air transport)
- Pre-existing socio-economic vulnerability of population in affected area
- Fraction of affected population made up of tourists (less local knowledge and thus more vulnerable)

While detailed modelling to quantify this risk is not possible, a qualitative assessment has been performed, in order to evaluate the likely significance of morbidity in the state (overall and also in terms of the individual factors listed above), as a result of the earthquake risks estimated.

It should be clearly noted that this is a *relative* assessment only (each District is compared to all other Districts in the State, and likewise for Blocks) rather than being assessed against an external standard or reference. Thus it can be stated with some confidence that one District is at a higher morbidity risk than another, but the actual level of that risk remains unknown.

A map showing the overall earthquake-dependent morbidity risk class estimated for each Block (left) and each District (upper right) in Uttarakhand is presented in Figure 3.50, along with a histogram of the class distribution for blocks (lower right). Further details for each District and Block are available in the corresponding Atlas volume.

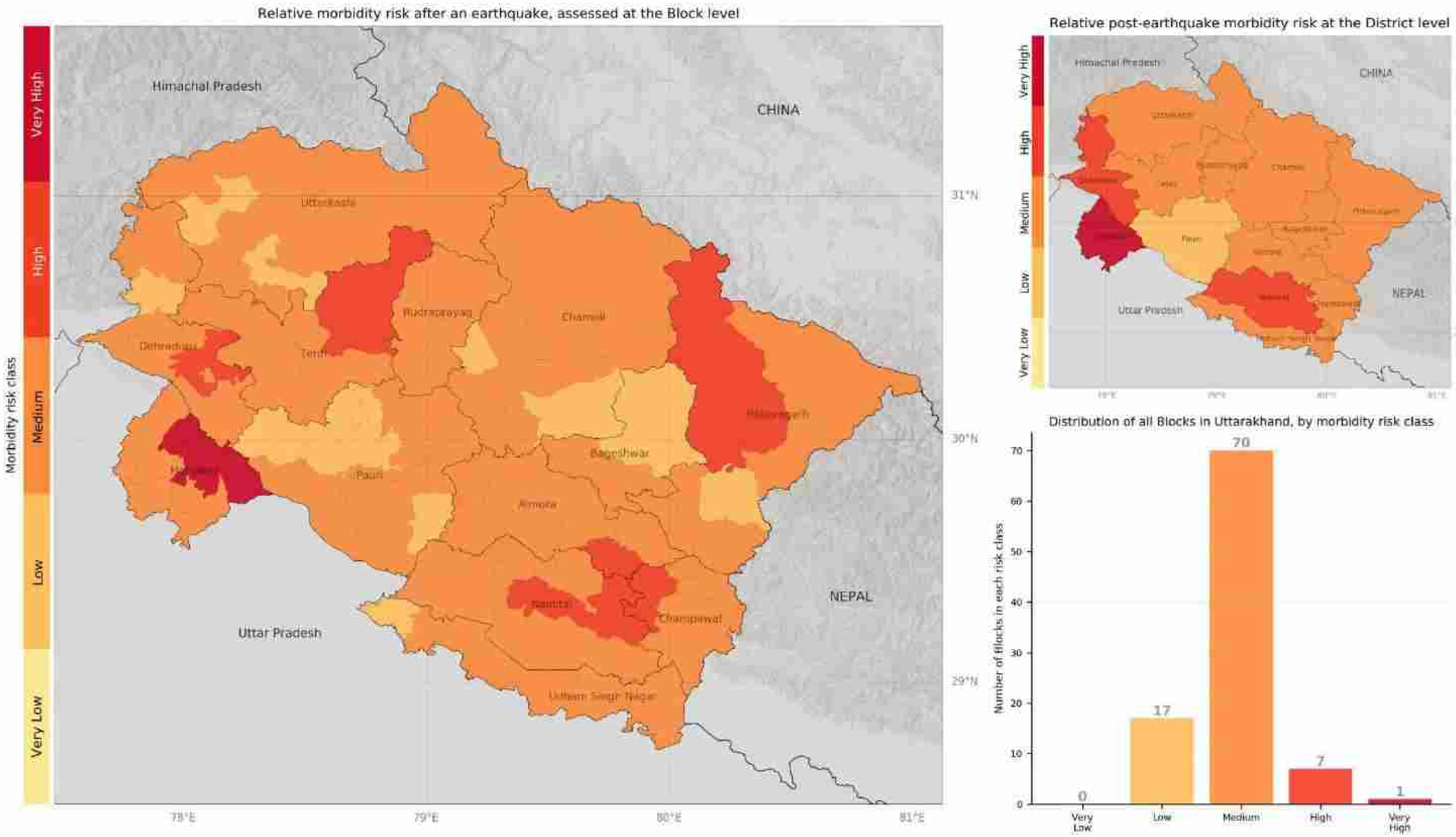

Figure 3.50: Overall earthquake-dependent morbidity risk classes estimated for all Blocks and Districts in Uttarakhand

3.3.12 Population losses due to earthquakes

Figure 3.51 shows the Average Annual Loss (AAL) of human lives (state residents) due to earthquake hazards.

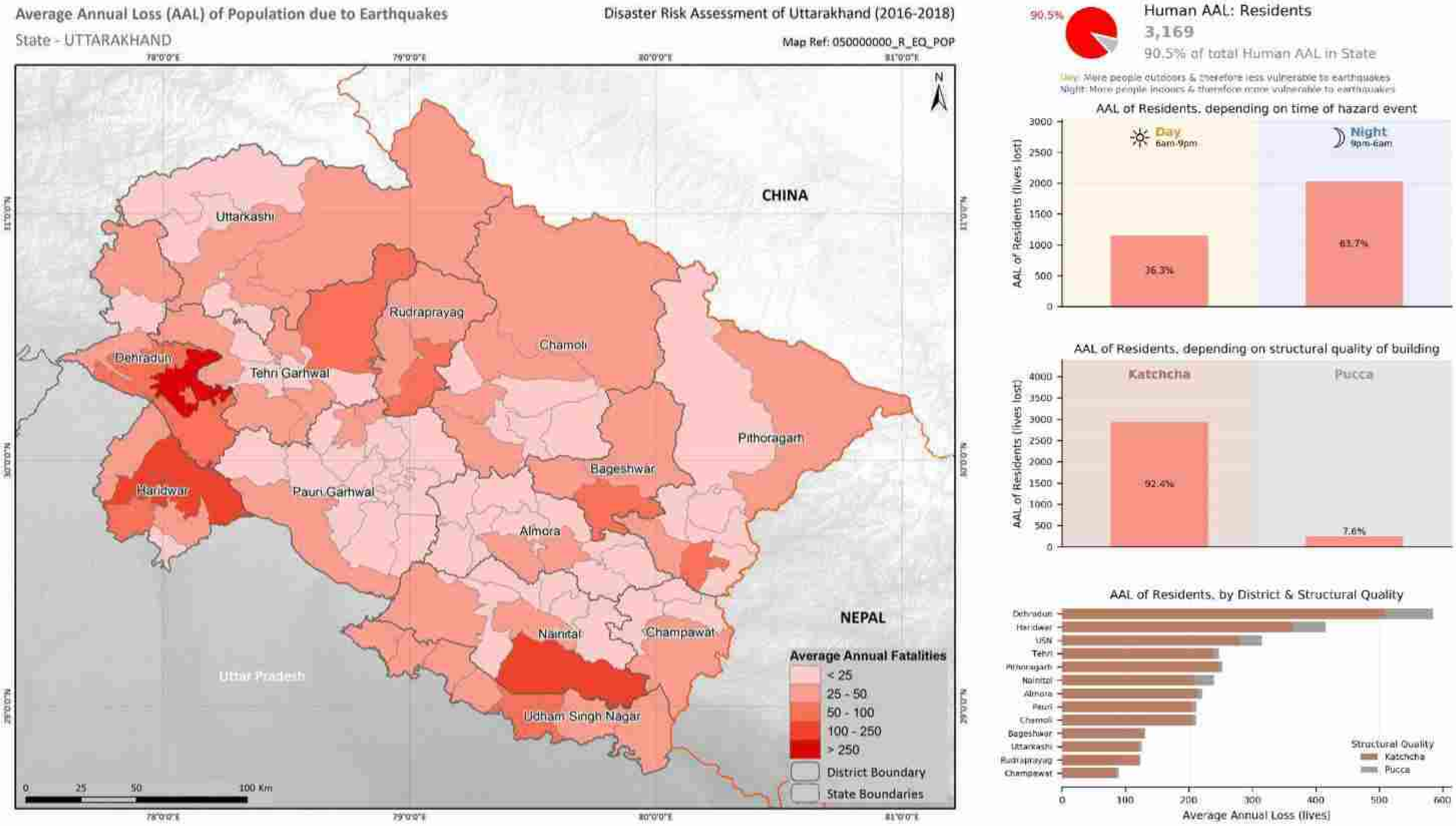

Figure 3.51: Average Annual Loss (AAL) of human lives (residents) due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.52 presents the PML curve for human lives (residents) in the state.

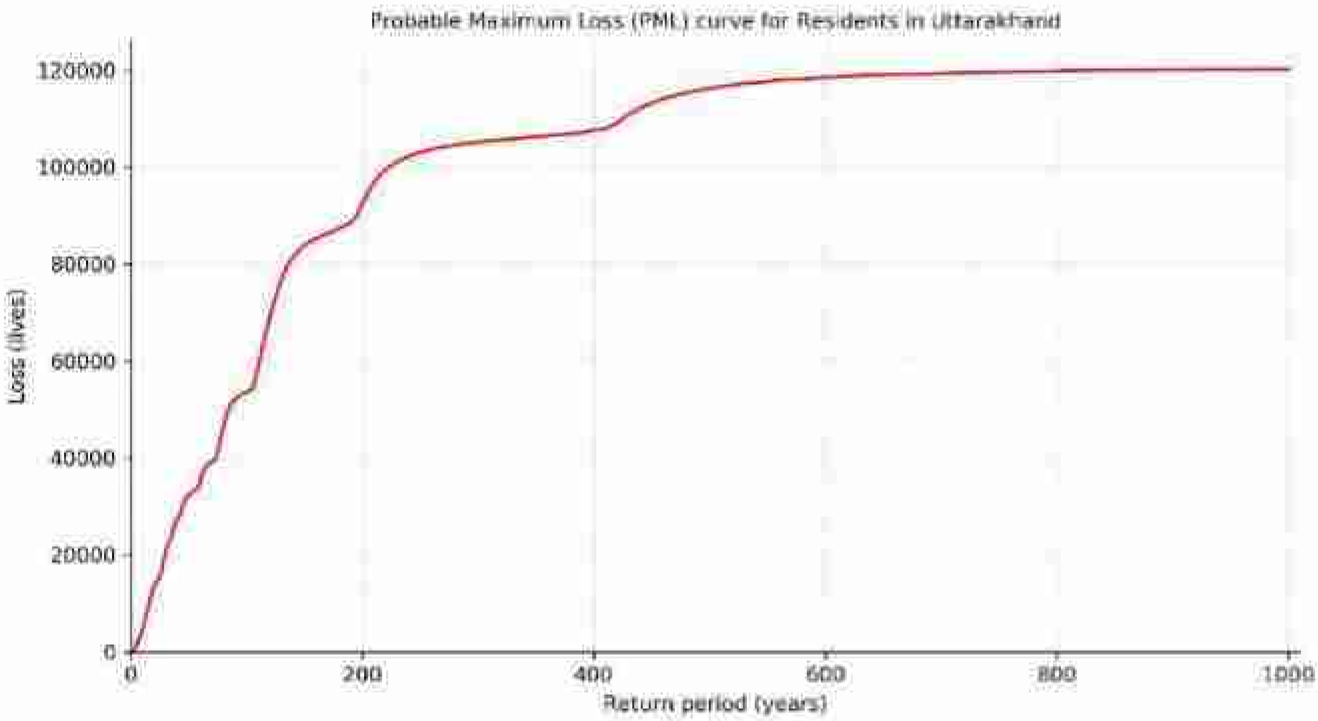

Figure 3.52: Probable Maximum Loss (PML) curve for human lives (residents) in Uttarakhand due to earthquakes

Figure 3.53 shows the Average Annual Loss (AAL) of human lives (tourists) due to earthquake hazards.

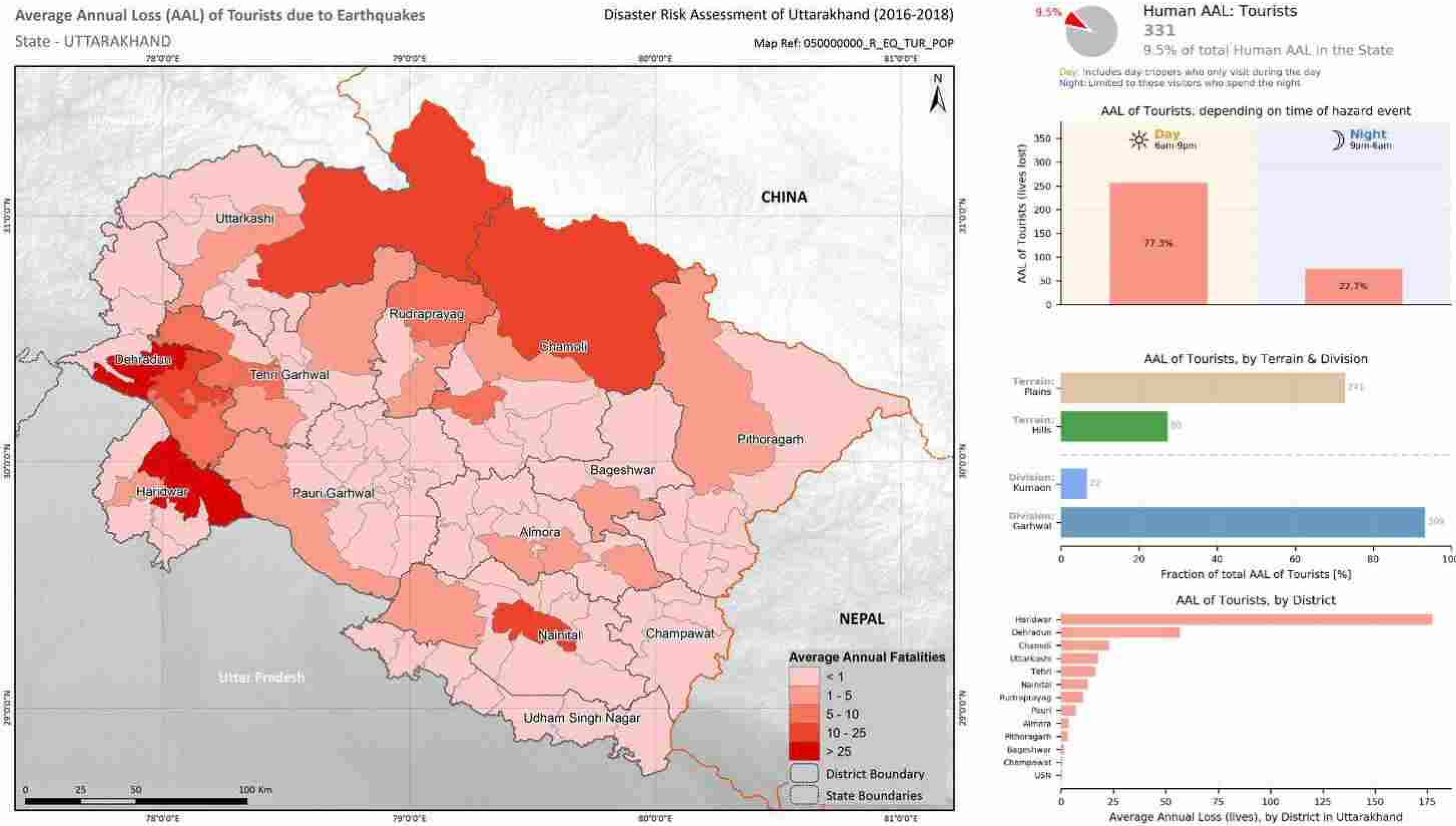

Figure 3.53: Average Annual Loss (AAL) of human lives (tourists) due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.54 presents the PML curve for human lives (tourist) in the state.

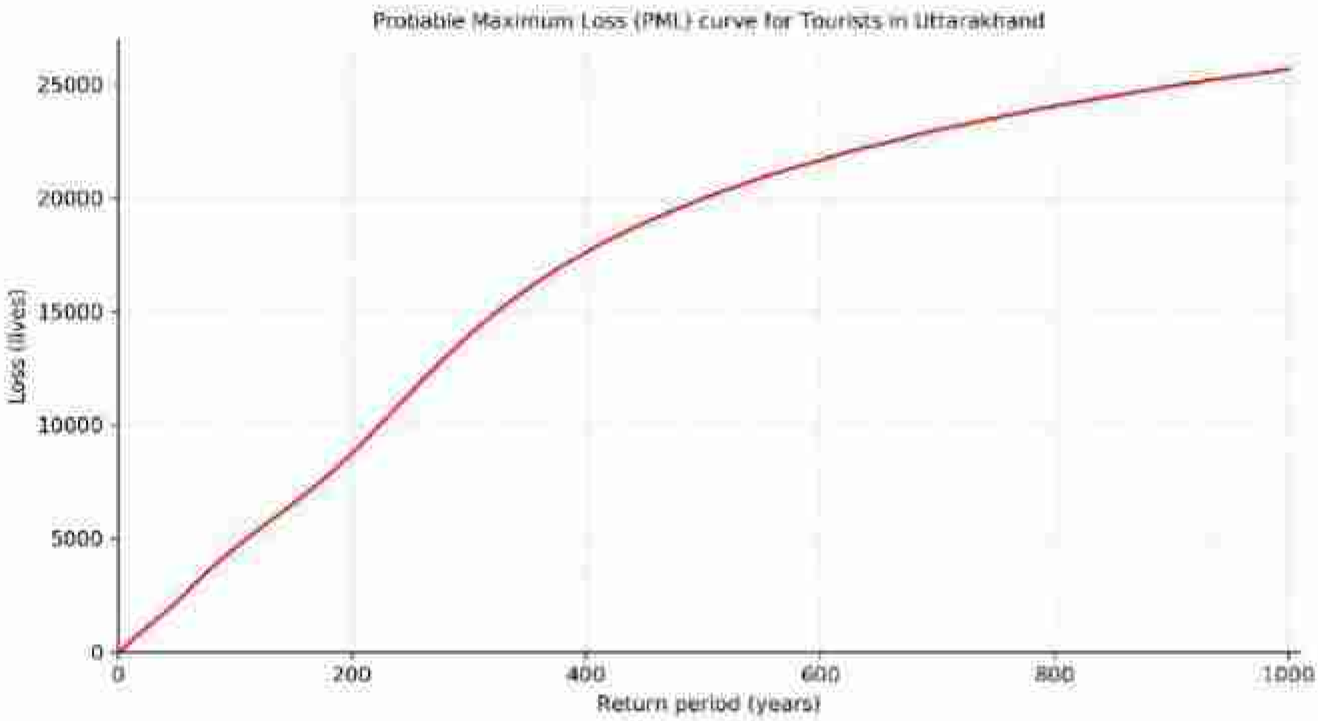

Figure 3.54: Probable Maximum Loss (PML) curve for human lives (tourists) in Uttarakhand due to earthquakes

3.3.13 Residential building losses due to earthquakes

Figure 3.55 shows the Average Annual Loss (AAL) of residential buildings due to earthquake hazards.

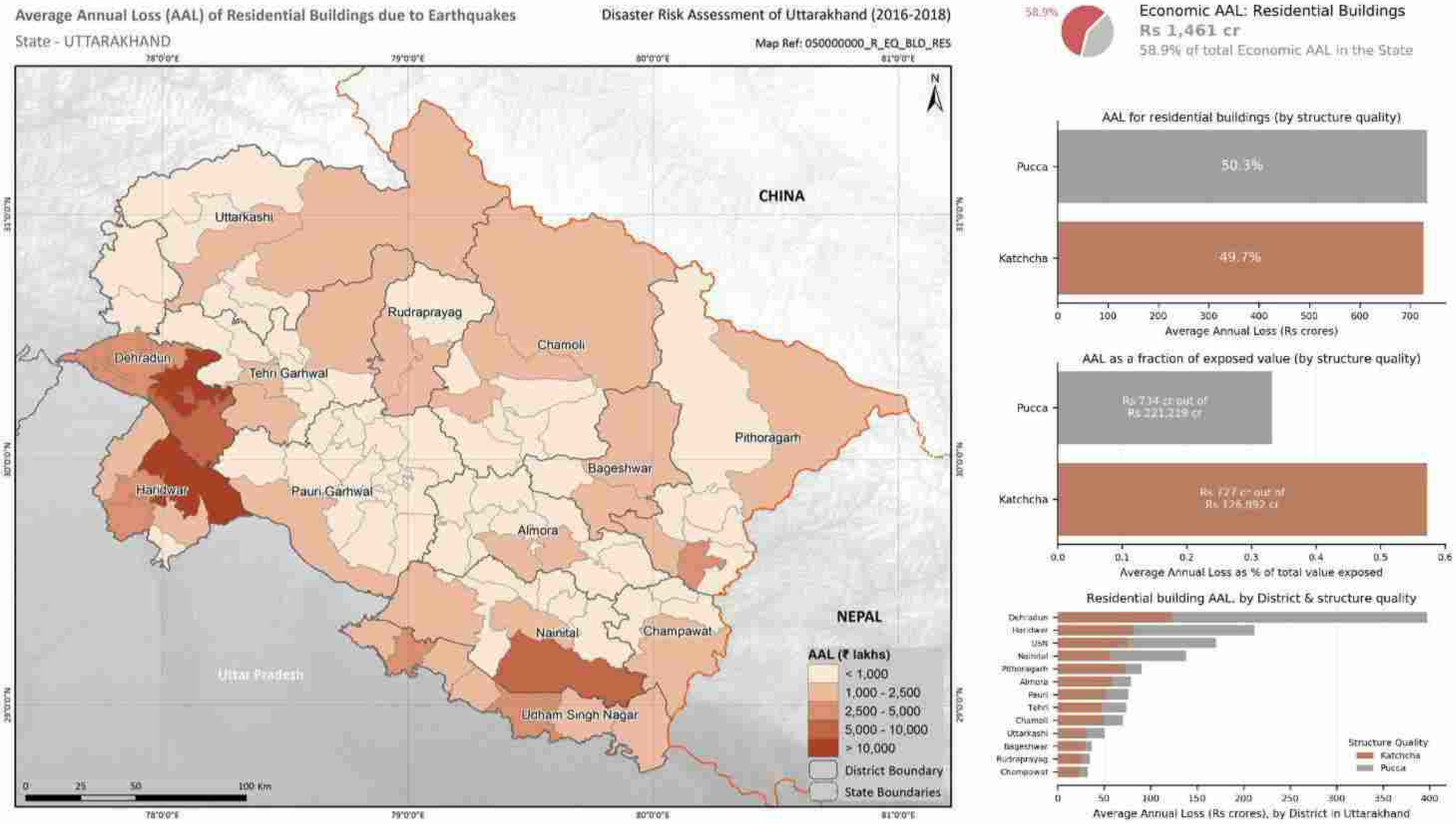

Figure 3.55: Average Annual Loss (AAL) of residential buildings due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.56 presents the PML curve for residential buildings in the state.

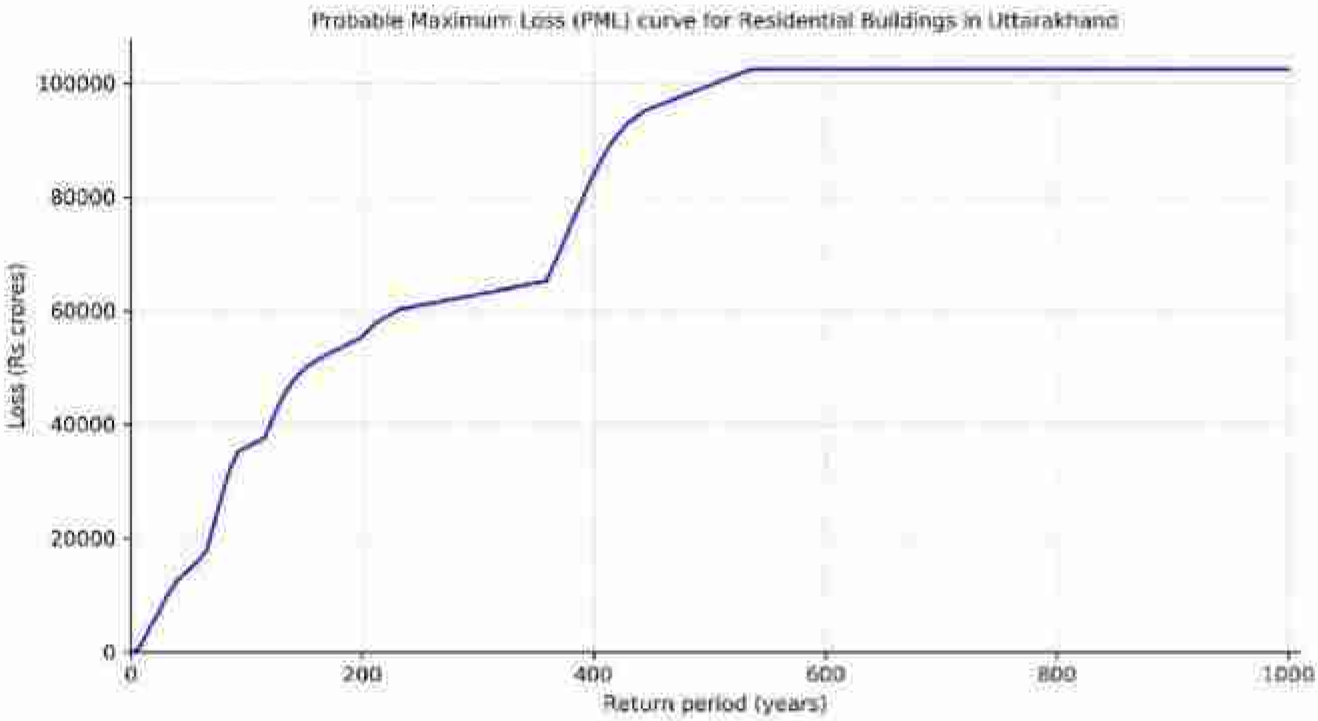

Figure 3.56: Probable Maximum Loss (PML) curve for residential buildings in Uttarakhand due to earthquakes

3.3.14 Critical building losses due to earthquakes

Figure 3.57 shows the Average Annual Loss (AAL) of critical buildings due to earthquake hazards.

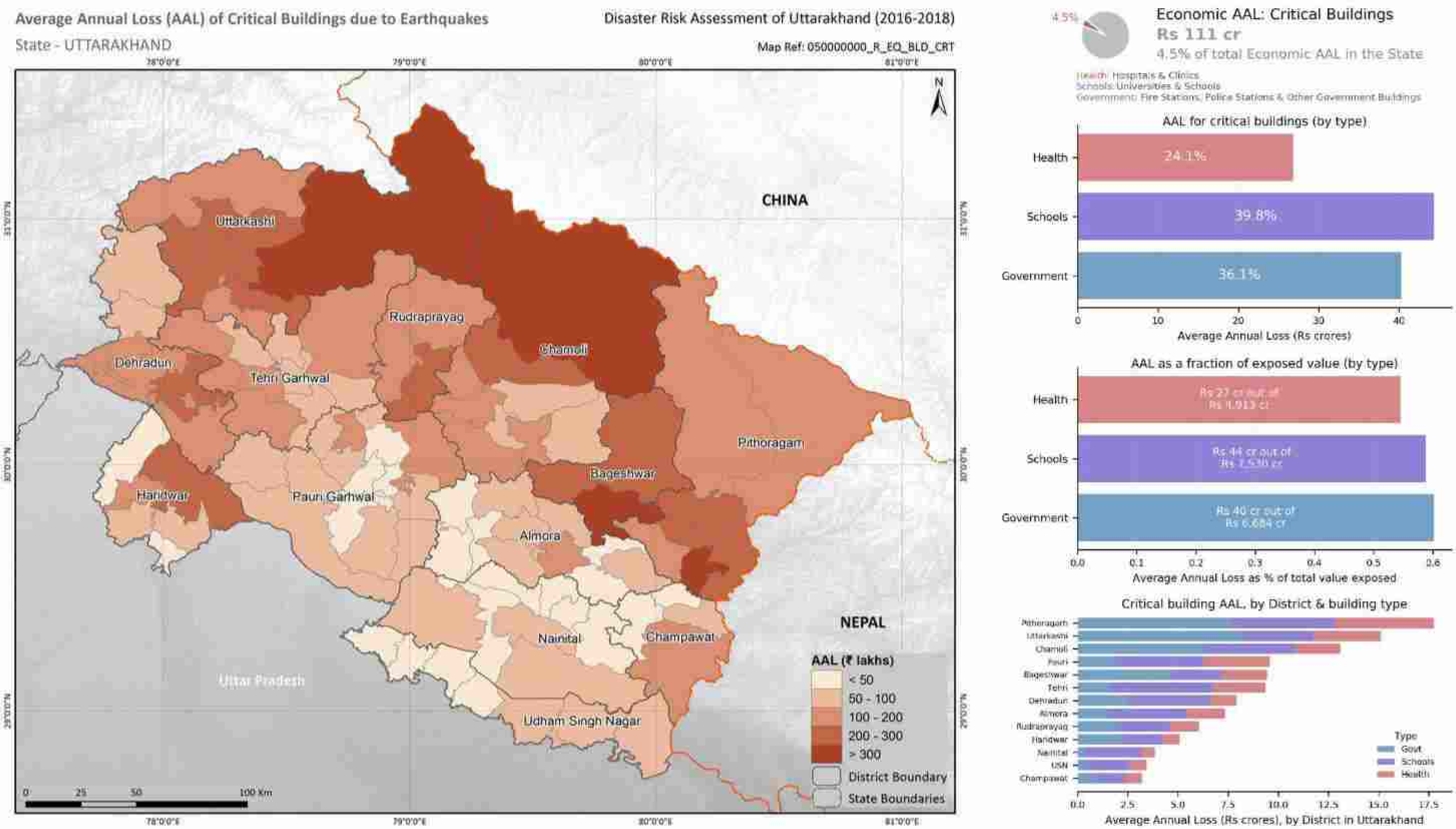

Figure 3.57: Average Annual Loss (AAL) of critical buildings due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3:58 presents the PML curve for critical buildings in the state.

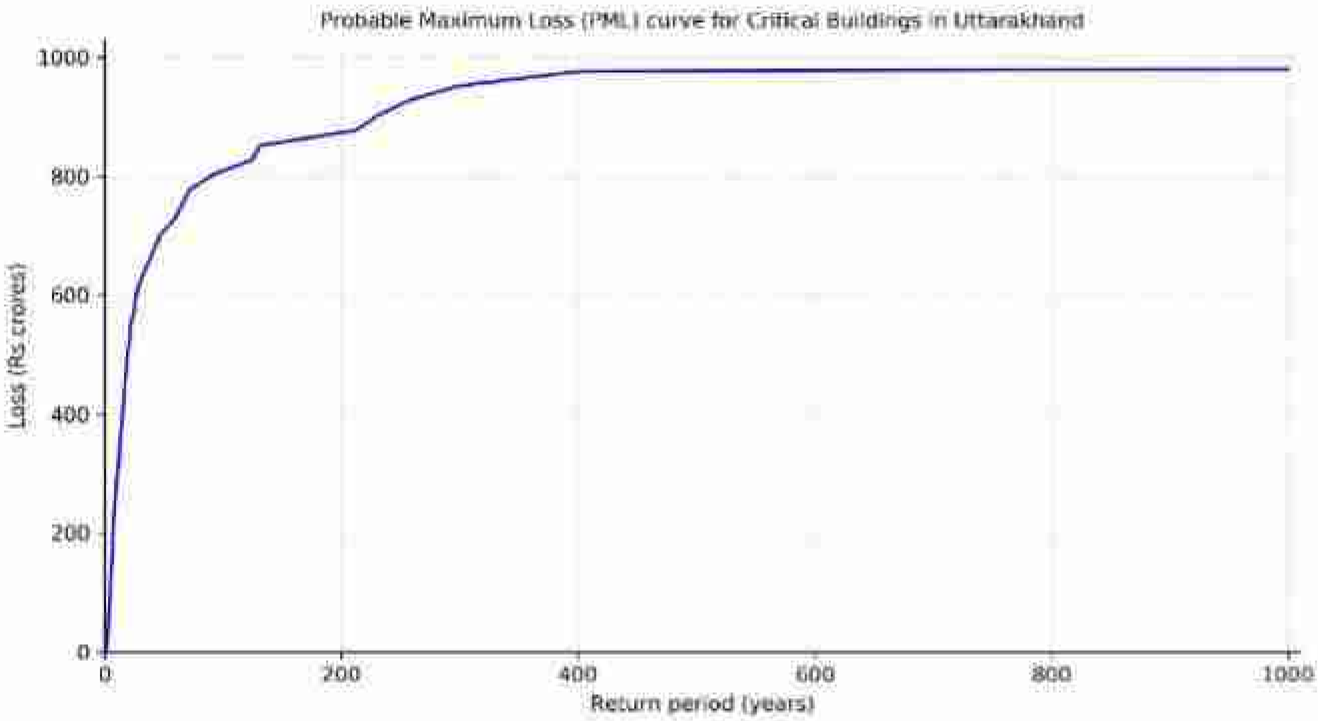

Figure 3.58: Probable Maximum Loss (PML) curve for critical buildings in Uttarakhand due to earthquakes

3.3.15 Transportation infrastructure losses due to earthquakes

Figure 3.59 shows the Average Annual Loss (AAL) of transportation infrastructure due to earthquake hazards.

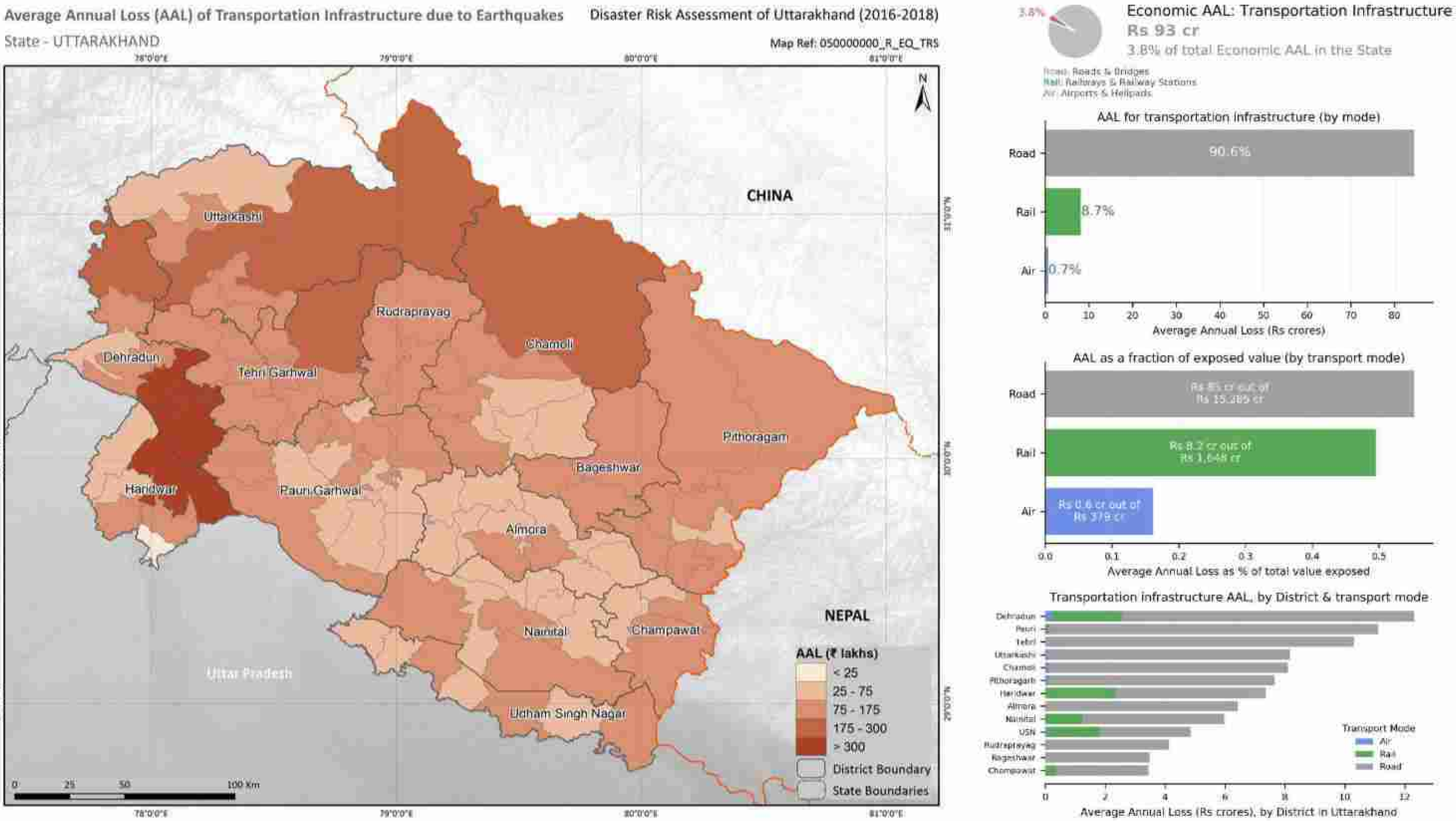

Figure 3.59: Average Annual Loss (AAL) of transportation infrastructure due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.60 presents the PML curve for transportation infrastructure in the state.

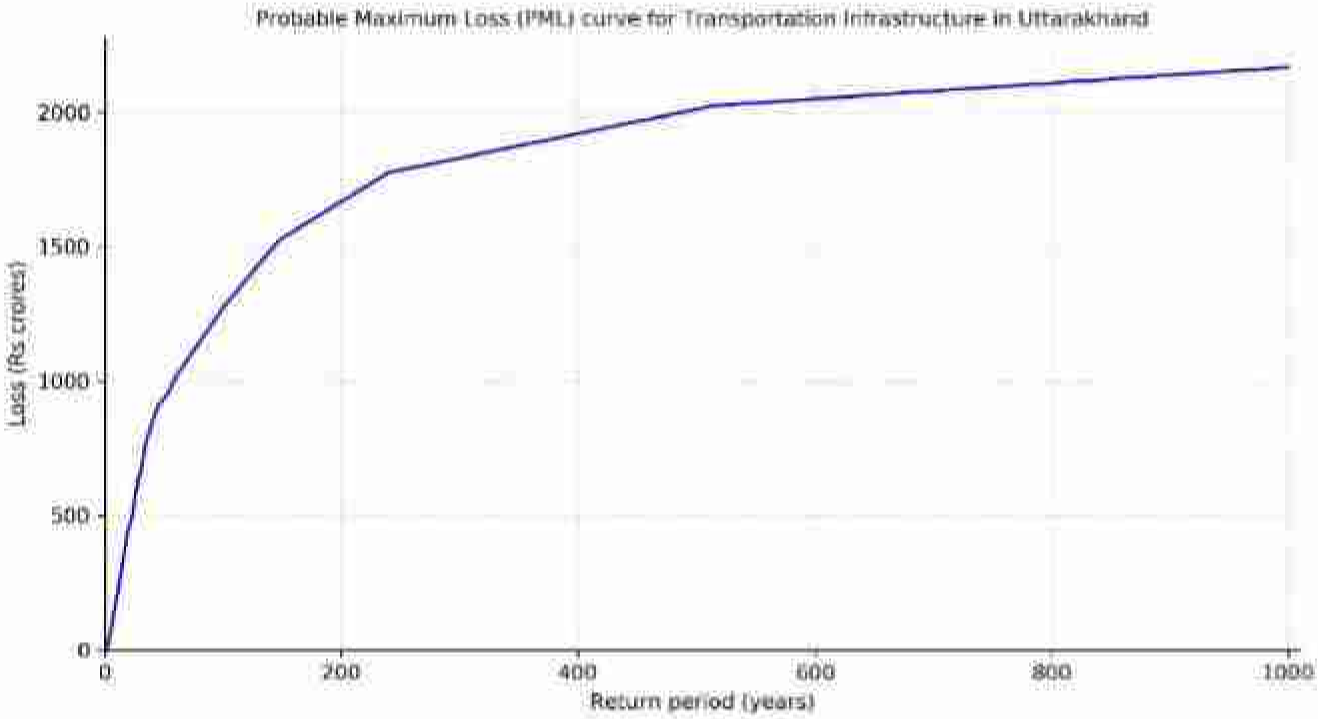

Figure 3.60: Probable Maximum Loss (PML) curve for transportation infrastructure in Uttarakhand due to earthquakes

3.3.16 Power infrastructure losses due to earthquakes

Figure 3.61 shows the Average Annual Loss (AAL) of power infrastructure due to earthquake hazards.

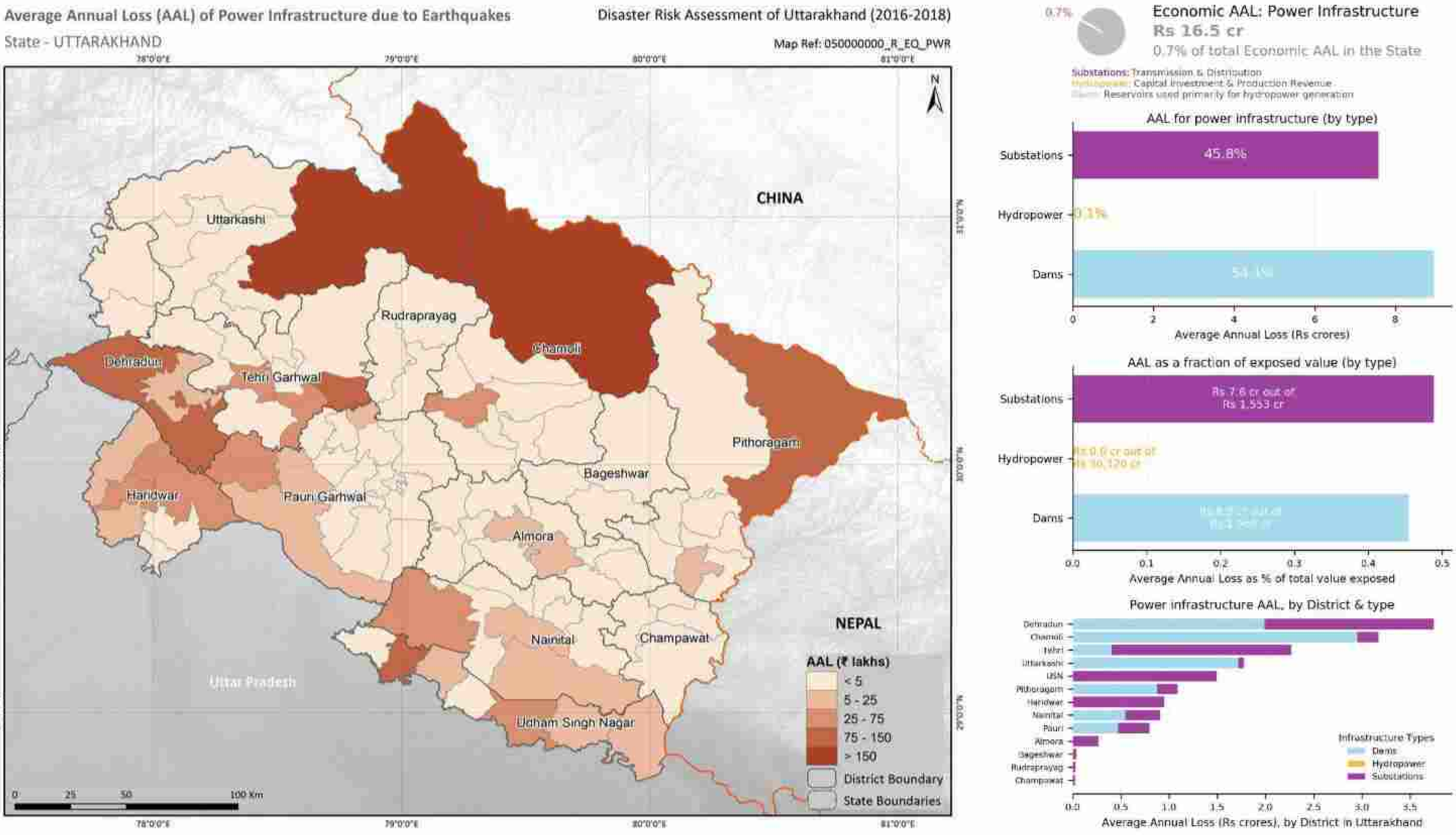

Figure 3.61: Average Annual Loss (AAL) of power infrastructure due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.62 presents the PML curve for power infrastructure in the state.

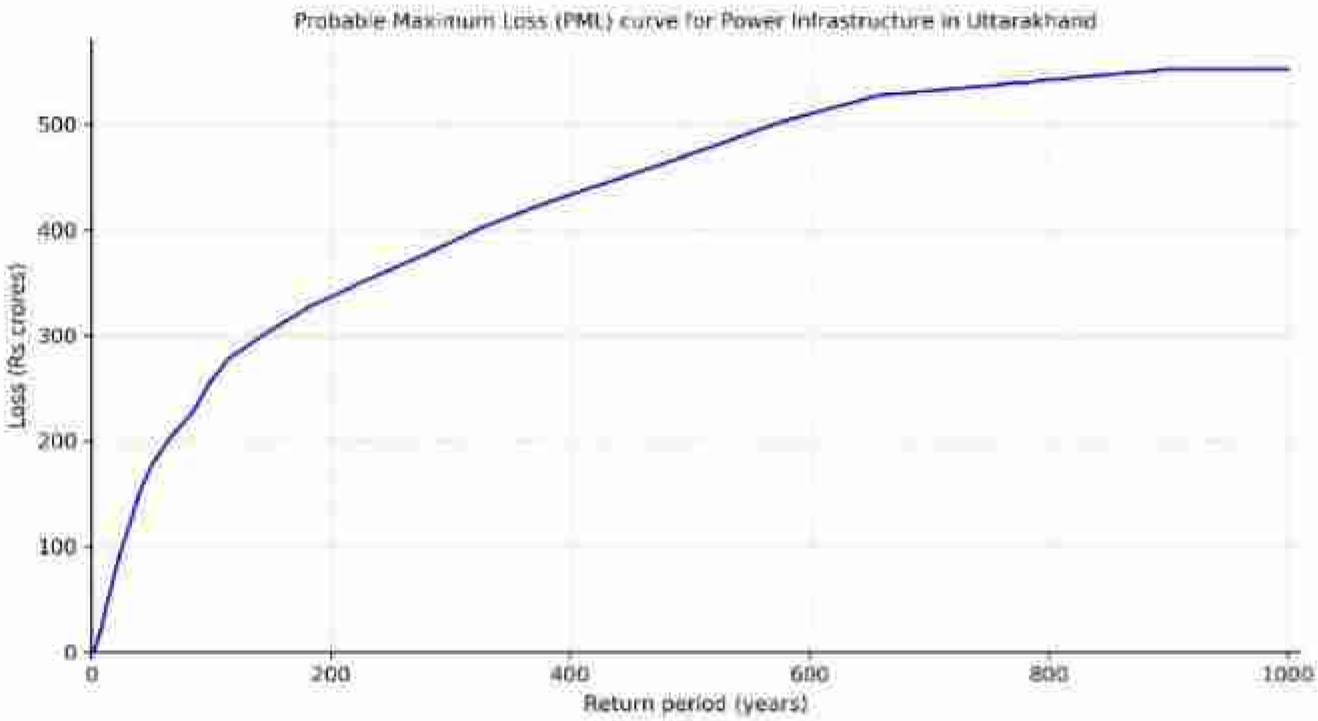

Figure 3.62: Probable Maximum Loss (PML) curve for power infrastructure in Uttarakhand due to earthquakes

3.3.17 Economic sector losses due to earthquakes

Figure 3.63 shows the Average Annual Loss (AAL) of agriculture (irrigation structures) due to earthquake hazards.

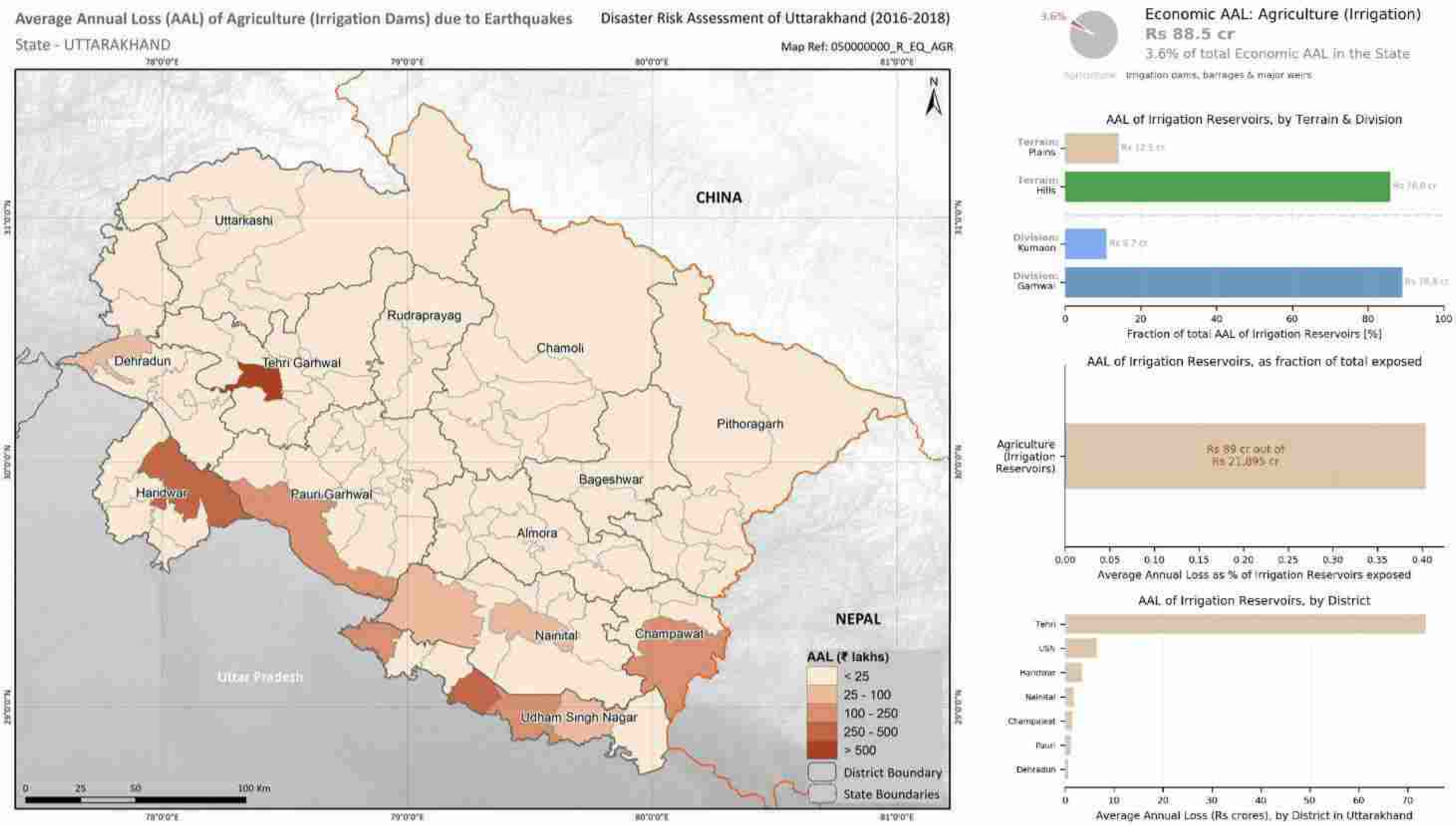

Figure 3.63: Average Annual Loss (AAL) of agriculture (irrigation structures) due to earthquakes

Figure 3.64 shows the Average Annual Loss (AAL) of industry, commerce and mining due to earthquake hazards.

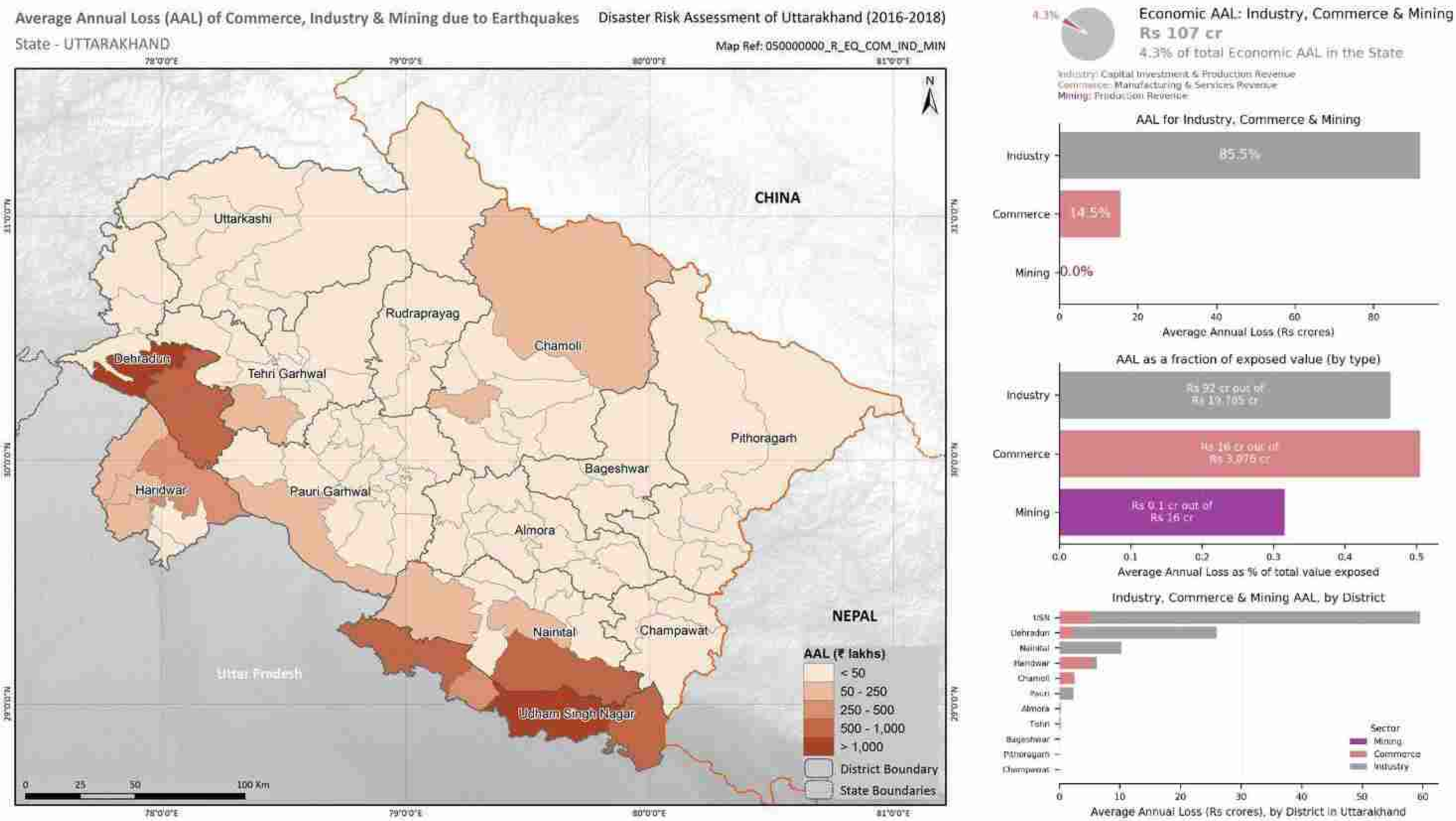

Figure 3.64: Average Annual Loss (AAL) of industry, commerce and mining due to earthquakes

Figure 3.65 shows the Average Annual Loss (AAL) of potential future tourism revenue due to earthquake hazards.

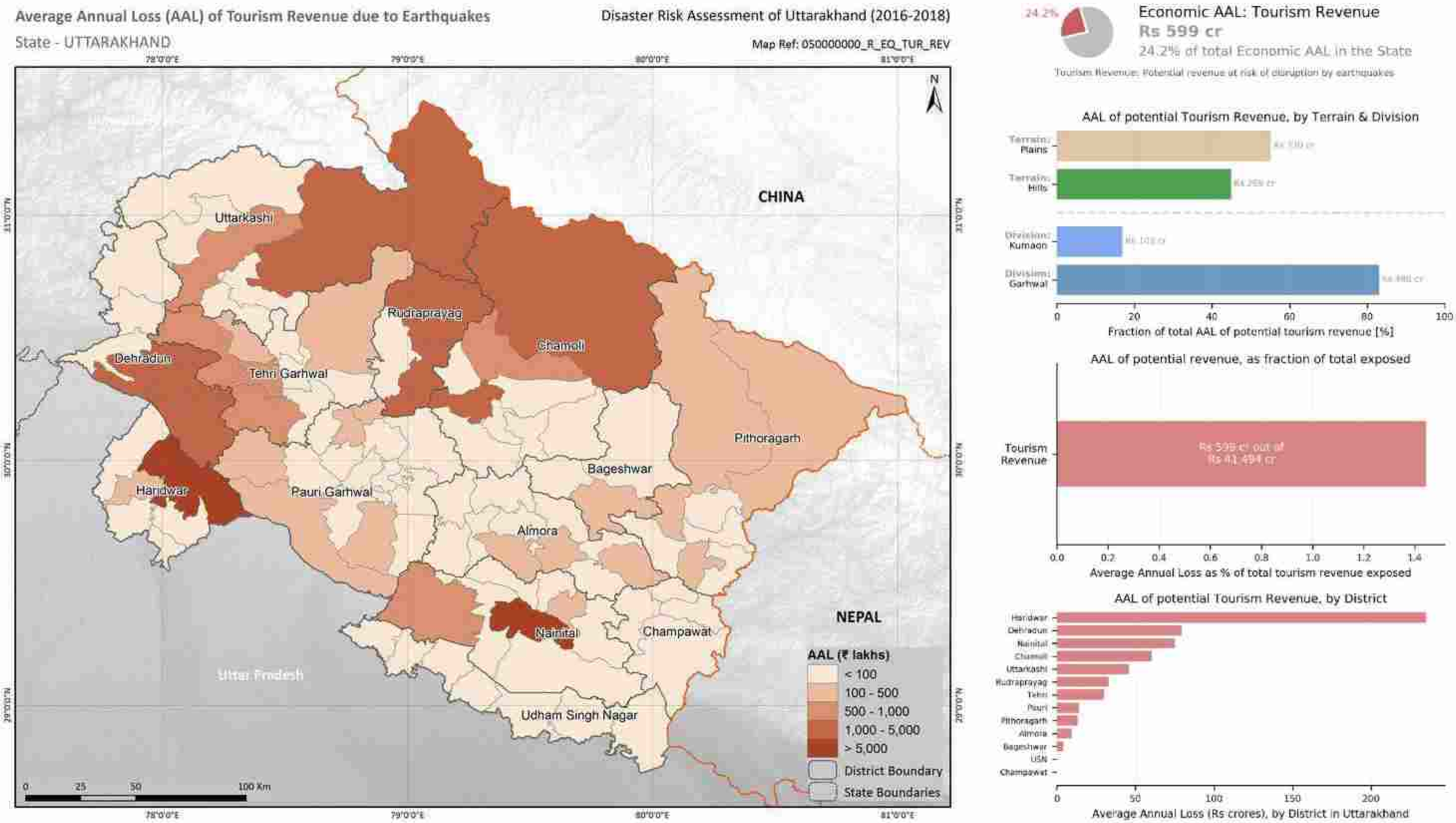

Figure 3.65: Average Annual Loss (AAL) of potential (future) tourism revenue due to earthquakes

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.66 presents the PML curve for economic sectors in Uttarakhand State, encompassing agriculture (irrigation dams only), industry, commerce, mining and tourism revenues.

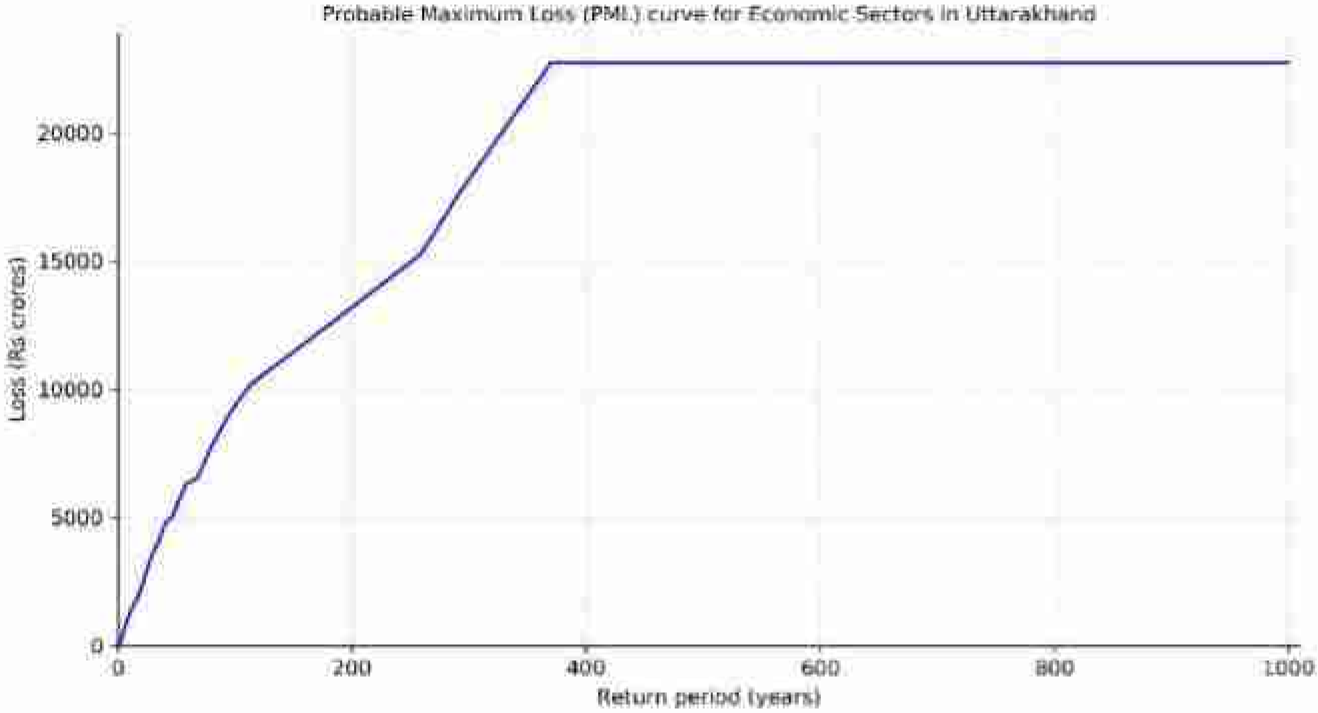

Figure 3.66: Combined Probable Maximum Loss (PML) curve for economic sectors in Uttarakhand due to earthquakes

3.4 Floods

Hazard Profile (Fluvial & Flash Floods)

Assessing flood hazards for Uttarakhand required two modelling approaches in order to capture the different types of flood that may pose a threat to people and property in the state. Fluvial (river) floods were modelled using basin-scale coupled 1D models (hydrological and hydrodynamic), based on long-term time-series of daily rainfall data. Flash floods and ponding due to short, intense, localised rainfall events were modelled using a 2D model, based on 6h design rainfall events. Further details regarding the fluvial flood and flash flood modelling approaches are provided in Volume 1, Chapter 2.

In the following sections, Volume 3.4.1 presents a map showing which of these approaches was used for different parts of the state. The main river network (modelled using the long-term basin-scale model) is indicated by the green and red lines (the different colours show the level of uncertainty in simulated results along that stretch, which is mostly a function of the underlying DEM quality). The remainder of the state was covered by the short-term localised model, capturing overland and gully flows, as well as rainfall-induced ponding. The map also shows digitised building clusters, as a simple indication of exposure, as well as glacial lakes which have been assessed to pose a threat related to Glacial Lake Outburst Floods (GLOFs).

In Volume 3.4.2, a map of flood depths which have a 100 year return period is presented, combining outputs from the two modelling approaches described above, in order to ensure the fullest possible coverage of the entire state. Over any 50 year period, a flood of this magnitude (or greater) has a 40% chance of occurring at least once. It is estimated that such a flood event would result in approximately 8.1% of the state being inundated to a depth of 0.3m or greater. This is illustrated in the plot below, breaking it down into six different inundation depth classes.

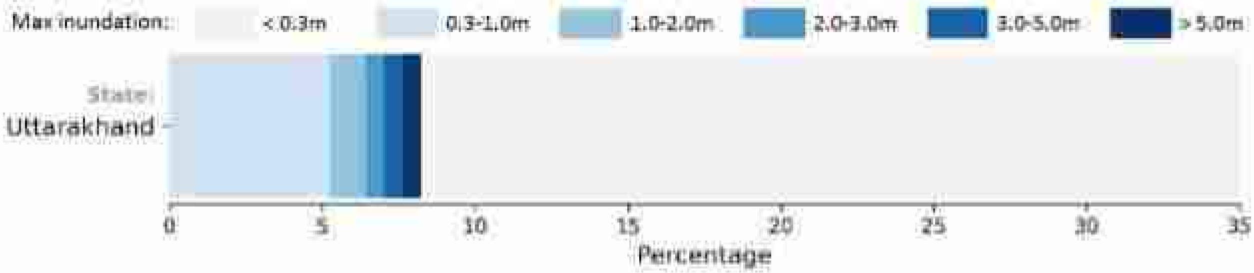

Figure 3.67: Proportions of state in different inundation depth ranges (based on a 100 year return period)

Based on the same analysis, the following page presents a ranking of all districts (left) and blocks (right) in the state of Uttarakhand, in terms of the percentage of their area expected to be inundated to a depth of 0.3m or higher during the 100 year return period flood.

As well as inundation depths, flow velocities are significant in evaluating the overall flood hazard, particularly in terms of the risk to people and buildings during flash flood events. The map in Volume 3.4.3 presents the flash flood hazard zones defined for Uttarakhand, based on both depth and flow velocity, following a widely used approach to hazard ratings developed by HR Wallingford *et al.* (2012).

The plot below summarises the proportion (by area) of Uttarakhand in each hazard zone, as a quick visual summary of its flash flood hazard profile.

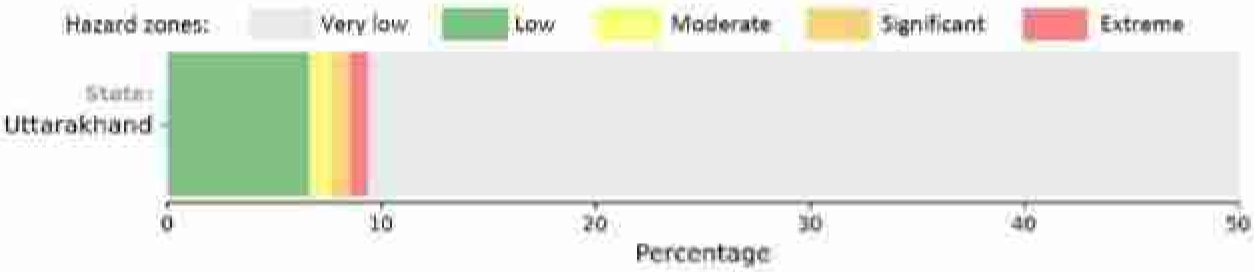

Figure 3.68: Proportions of state in different flash flood hazard zones (based on a 100 year return period)

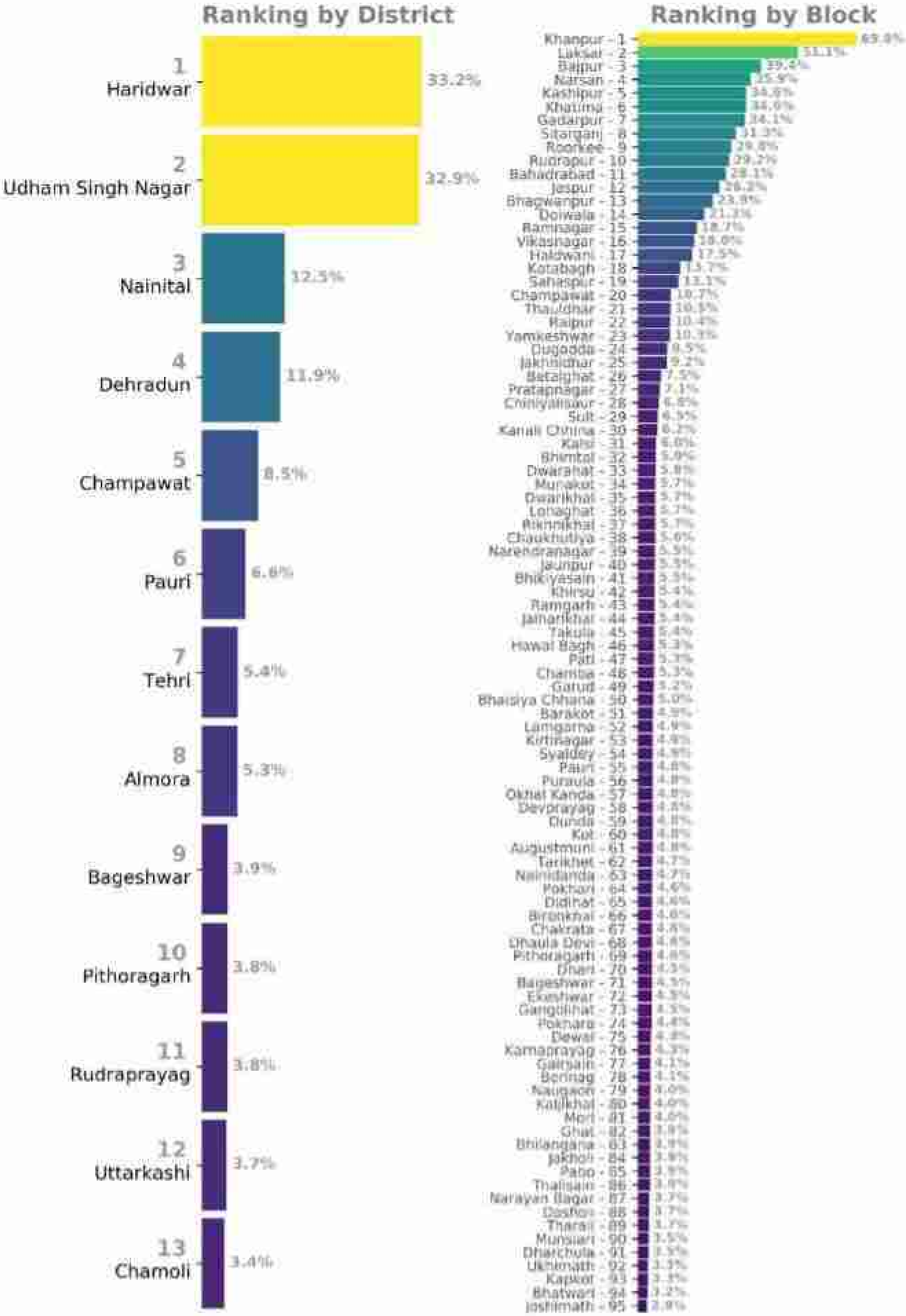

Figure 3.88: Ranking of districts (left) and blocks (right), based on proportion inundated to 0.3m or more

3.4.1 Flood hazard modelling overview map

The map below summarises flood model coverage and confidence in Uttarakhand, as well as showing glacial lakes in the state which have been assessed as breach-prone.

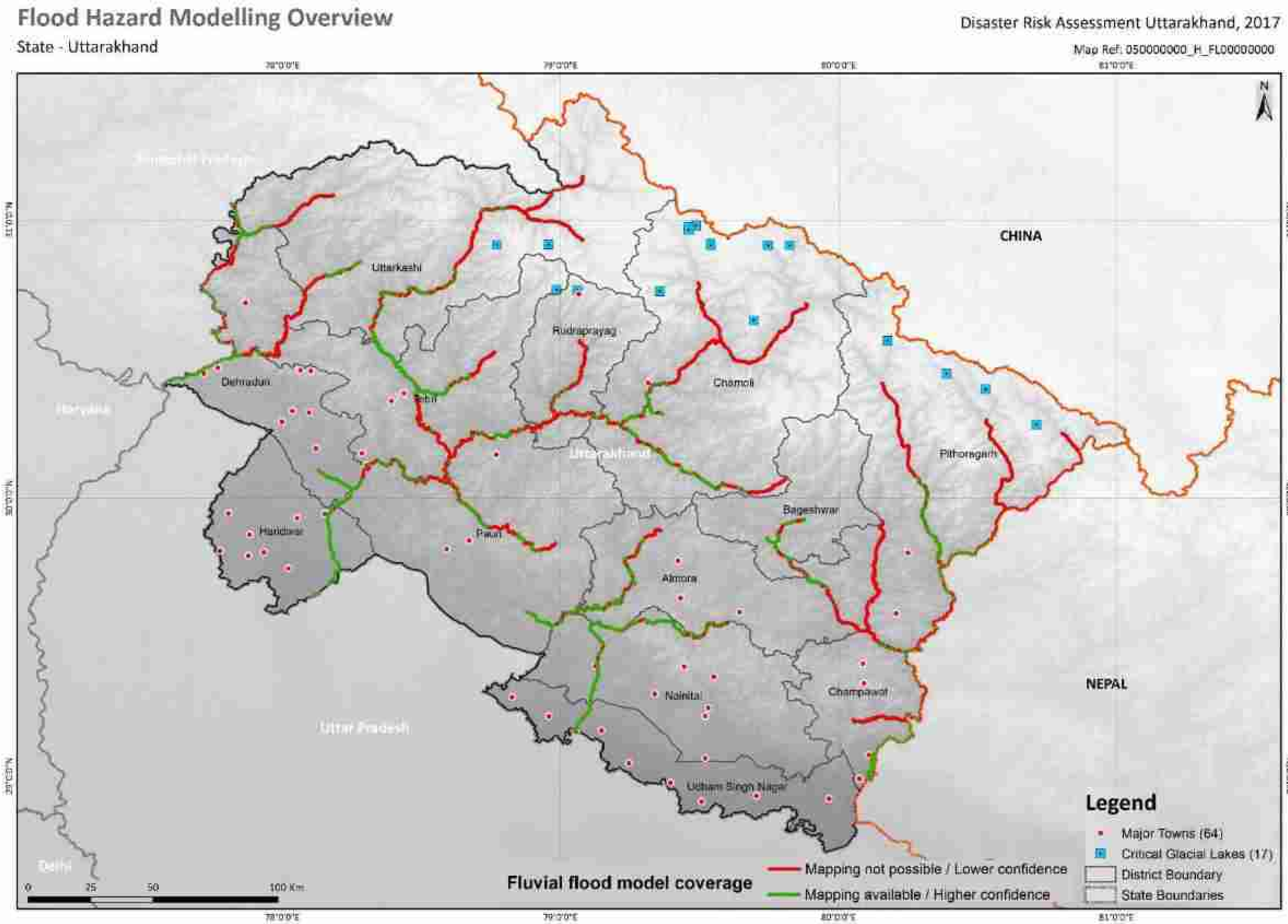

Figure 3.70: Overview of flood modelling approach for Uttarakhand, as well as other pertinent spatial features

3.4.2 Flood hazard map (inundation depths): 100 year return period

Simulated flood inundation depths with a return period of 100 years are mapped below for Uttarakhand, based on a combination of results from both hazard models described above.

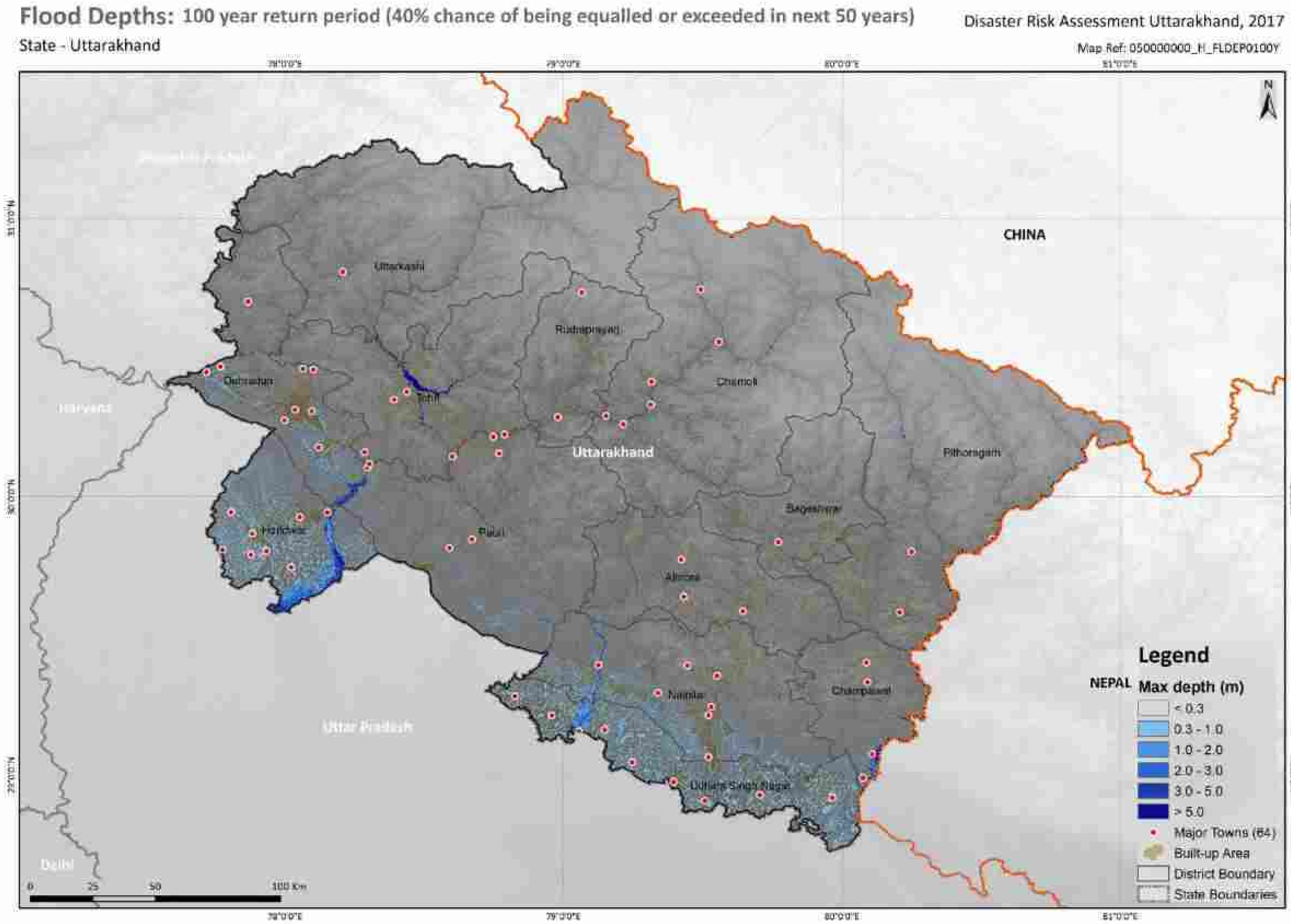

Figure 3.71: Simulated flood depths in Uttarakhand with a return period of 100 years

3.4.3 Flash flood hazard zones

The map below presents flash flood hazard zones delineated for Uttarakhand, based on results from the short-term localised model and accounting for both flood depths and flow velocities.

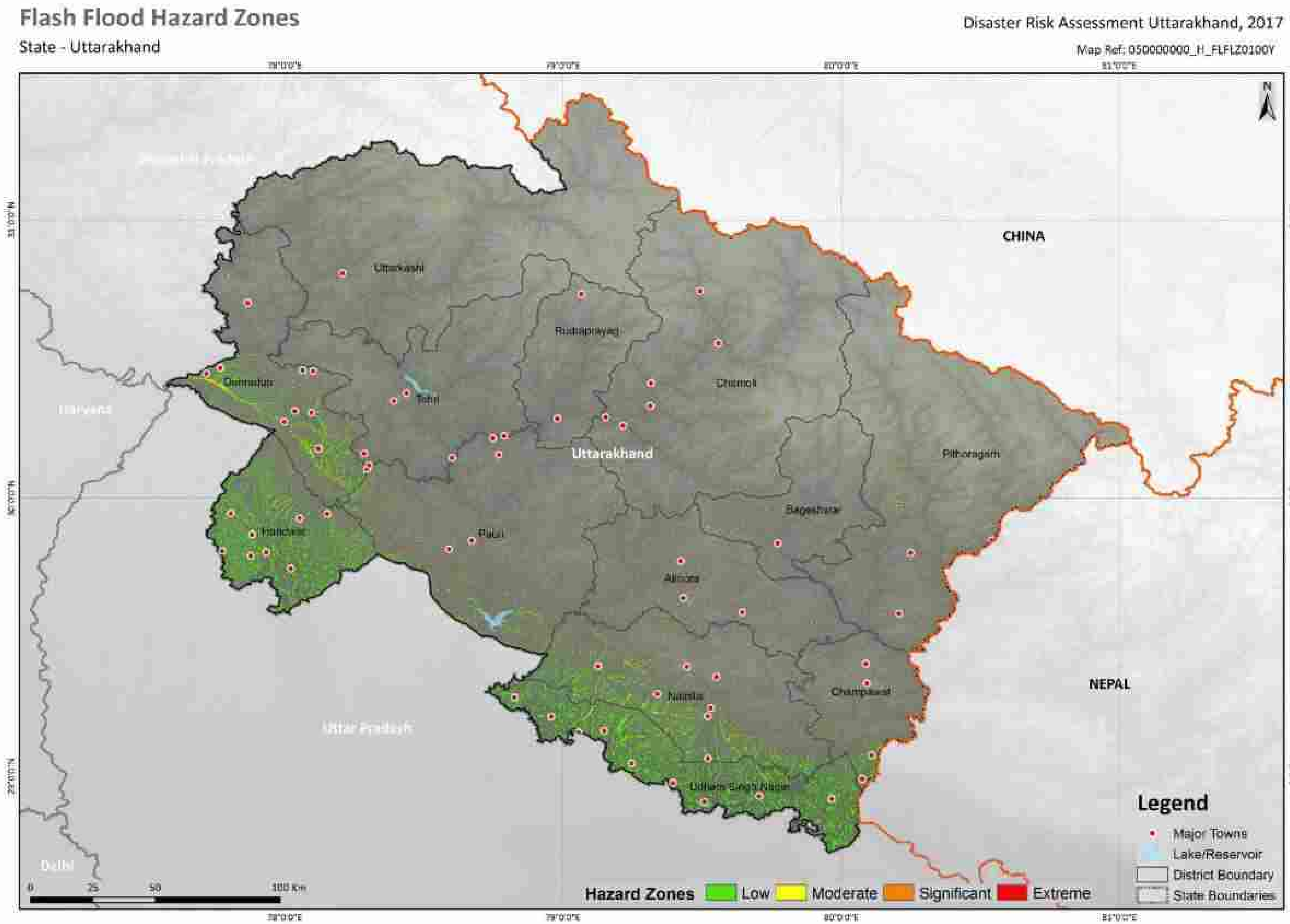

Figure 3.72: Flash flood hazard zones in Uttarakhand, based on simulated flood depths and velocities

Exposure Profile (Fluvial & Flash Floods)

This section presents a summary of the state's exposure to flood hazards, in terms of both fluvial/ponding flood depths and flash floods hazards (which are based on flow velocity as well as depth). Rather than estimating losses, the exposure assessment only looks at the extent to which people and economic assets are exposed to different hazard intensities, providing a useful preliminary indication of impact (which isn't subject to the uncertainties associated with economic valuation and vulnerability functions).

Figure 3.73 visualises the exposure of all portfolios to fluvial/ponding flood depths, in terms of the percentages of each population group or economic asset exposed to "limited" depths (<0.3m) as opposed to "significant" depths (≥0.3m), with reference to 100 year return period flood depths.

Figure 3.73: Visual summary of the State's overall exposure to flood depths with a 100 year return period

Figure 3.74 visualises the exposure of all portfolios to flash flood hazard zones, in terms of the percentages of each population group or economic asset exposed to "limited" hazards (only the 'Low' zone) as opposed to "significant" hazards (all zones higher than 'Low'), with reference to 100 year return period flood depths and flow velocities. As described in the Hazard Profile section of this Volume, flash flood hazard zones were defined based on both maximum flood depths and flow velocities, following a widely used approach developed by HR Wallingford *et al.* (2012).

Figure 3.74: Visual summary of the State's overall exposure to flash flood hazard zones with a 100 year return period

In the sections which follow, each portfolio will be considered separately, showing its exposure to floods in terms of both flood depth ranges and flash flood hazard zones (in each case based on the 100 year return period flood depths and flow velocities).

3.4.4 Population exposure to floods (fluvial and flash)

Figure 3.75 shows the exposure of the resident population to flood depths with a return period of 100 years. Note that a comparison of day-time versus night-time exposure is made, based on assumptions regarding the spatial distribution of the population at different times (with more people likely to be in built-up areas during the night).

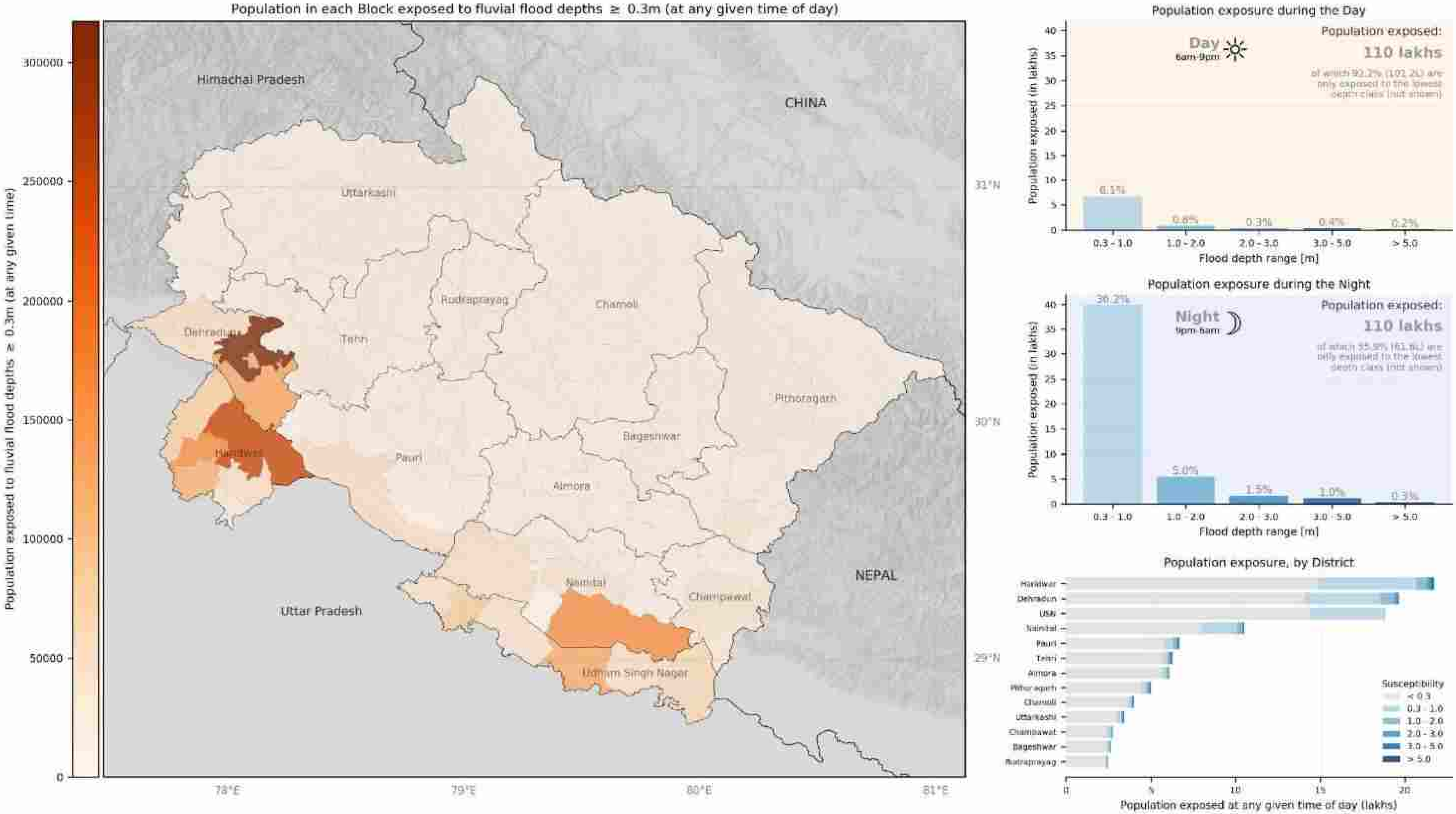

Figure 3.75: Visual summary of resident population exposed to flood depths with a 100 year return period

Figure 3.76 shows the exposure of the resident population to flash flood hazards with a return period of 100 years. Note that a comparison of day-time versus night-time exposure is made, based on assumptions regarding the spatial distribution of the population at different times (with more people likely to be in built-up areas during the night).

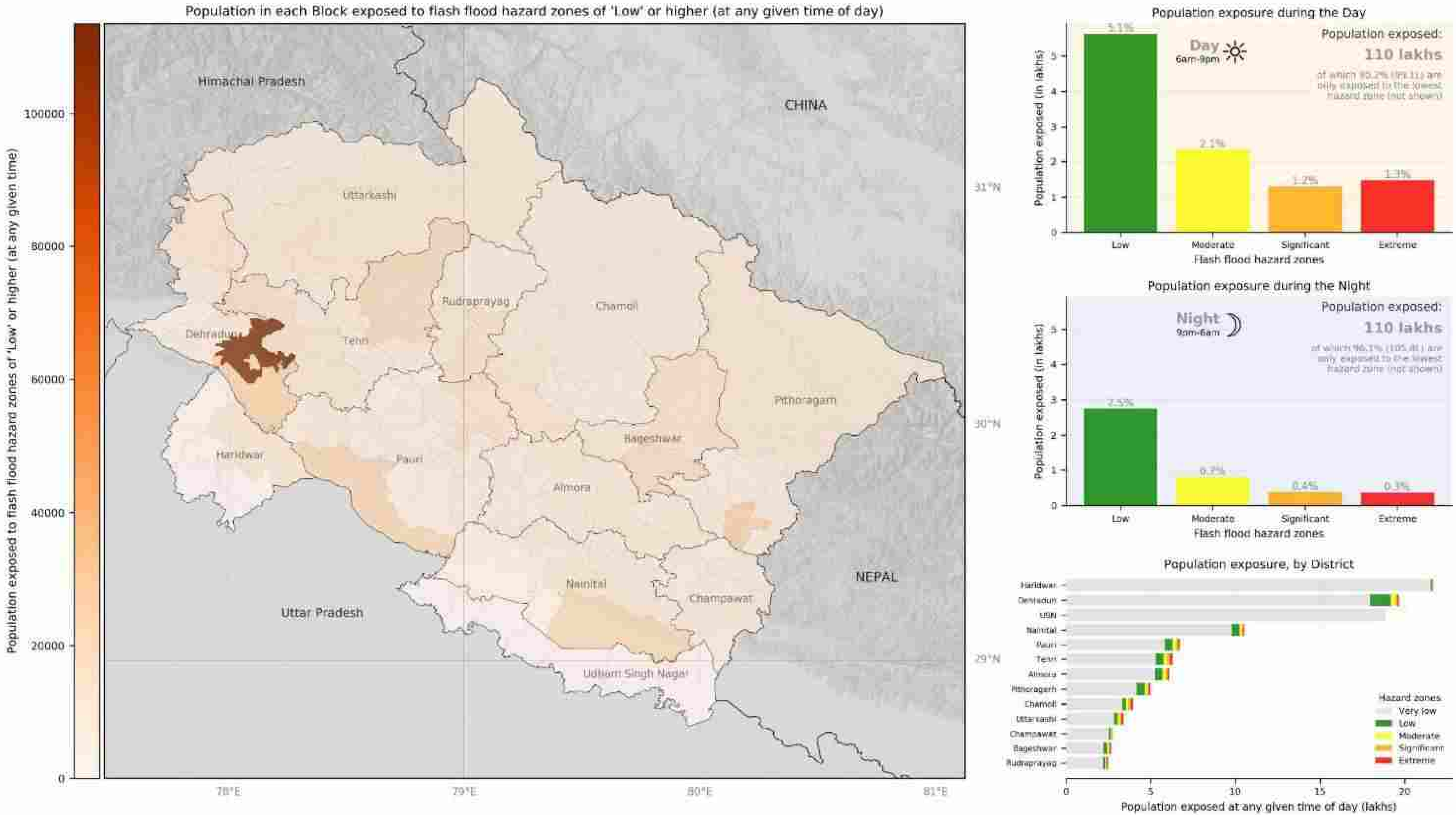

Figure 3.76: Visual summary of resident population exposed to flash flood hazard zones with a 100 year return period

Figure 3.77 shows the exposure of tourists to flood depths with a return period of 100 years. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values). As for the resident population, a comparison of day-time versus night-time exposure is made, based on assumptions regarding the spatial distribution of tourists (some of whom are just day-trippers) at different times.

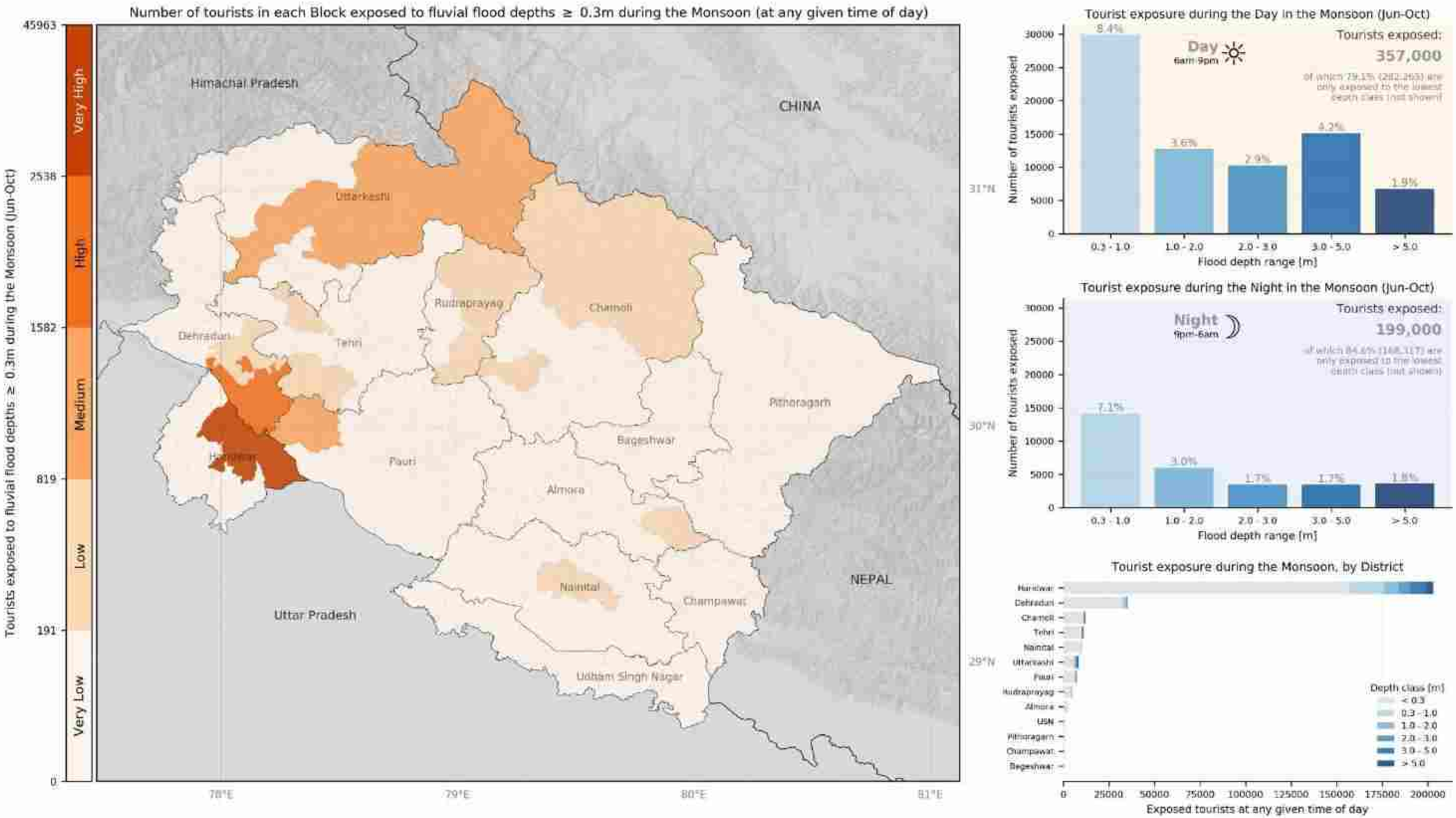

Figure 3.77: Visual summary of tourist population exposed to flood depths with a 100 year return period

Figure 3.78 shows the exposure of tourists to flash flood hazards with a return period of 100 years. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values). As for the resident population, a comparison of day-time versus night-time exposure is made, based on assumptions regarding the spatial distribution of tourists (some of whom are just day-trippers) at different times.

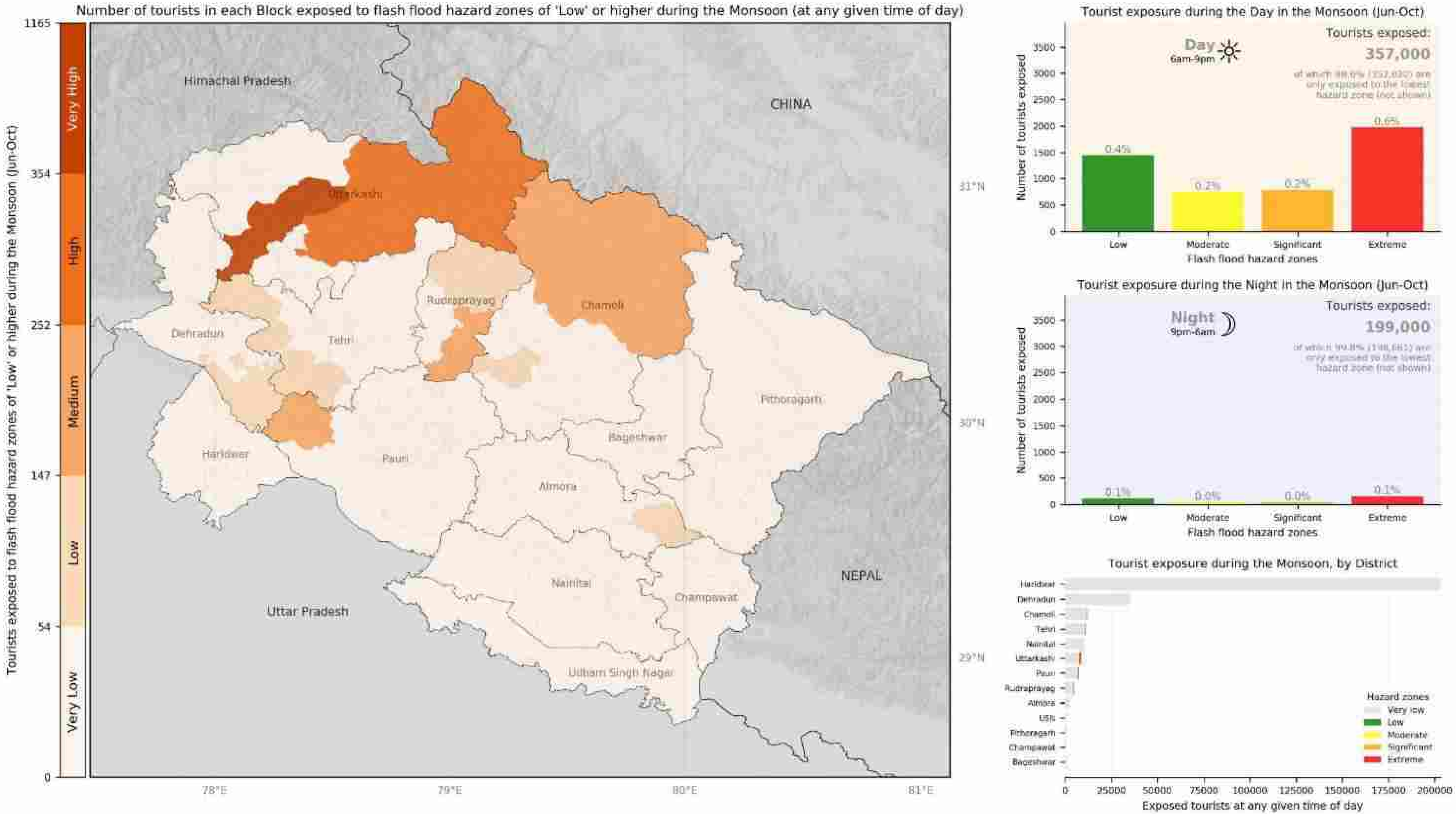

Figure 3.78: Visual summary of tourist population exposed to flash flood hazard zones with a 100 year return period

3.4.5 Residential building exposure to floods (fluvial and flash)

Figure 3.79 shows the exposure of residential buildings to flood depths with a return period of 100 years.

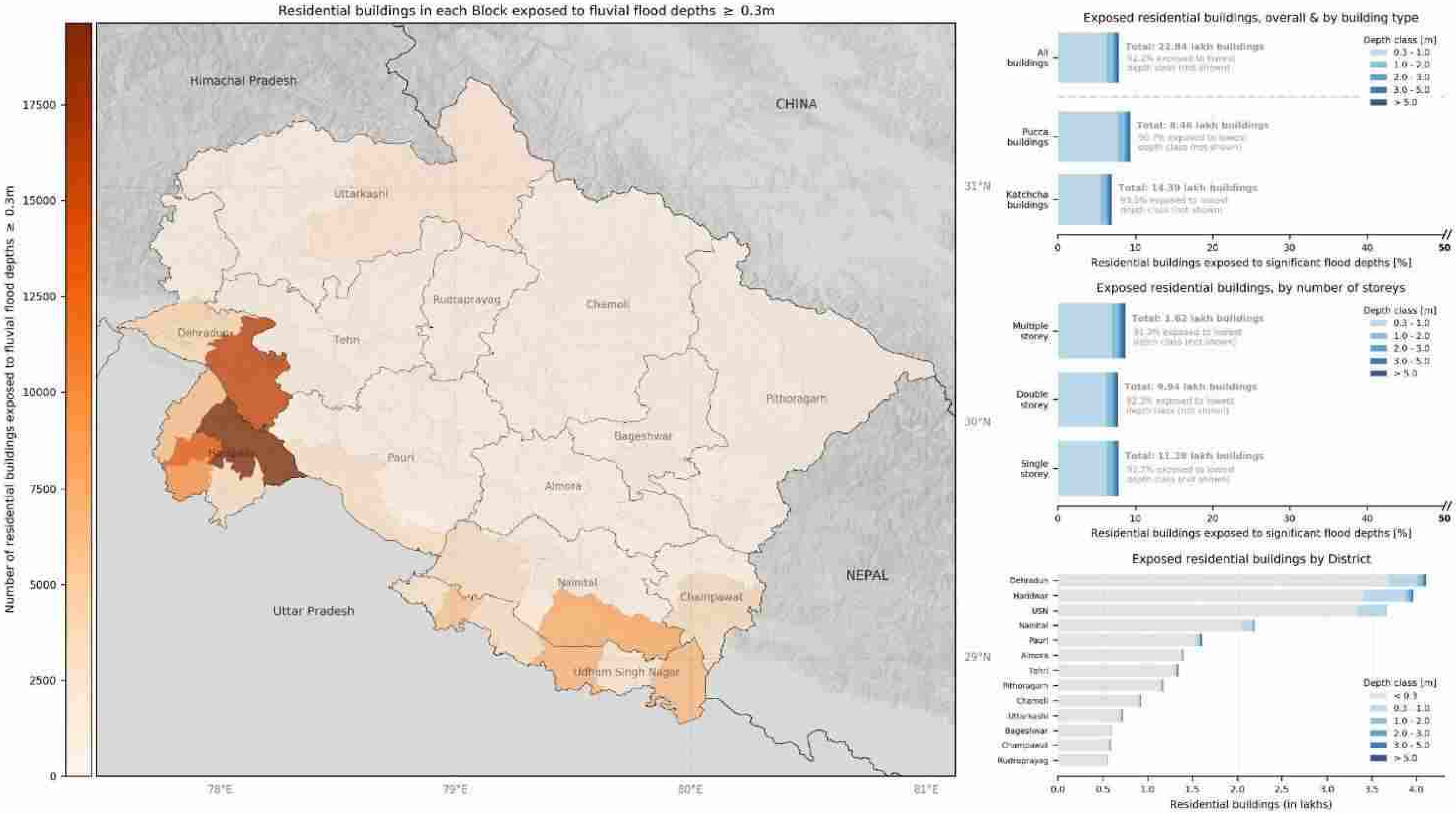

Figure 3.79: Visual summary of residential buildings exposed to flood depths with a 100 year return period

Figure 3.80 shows the exposure of residential buildings to flash flood hazards with a return period of 100 years.

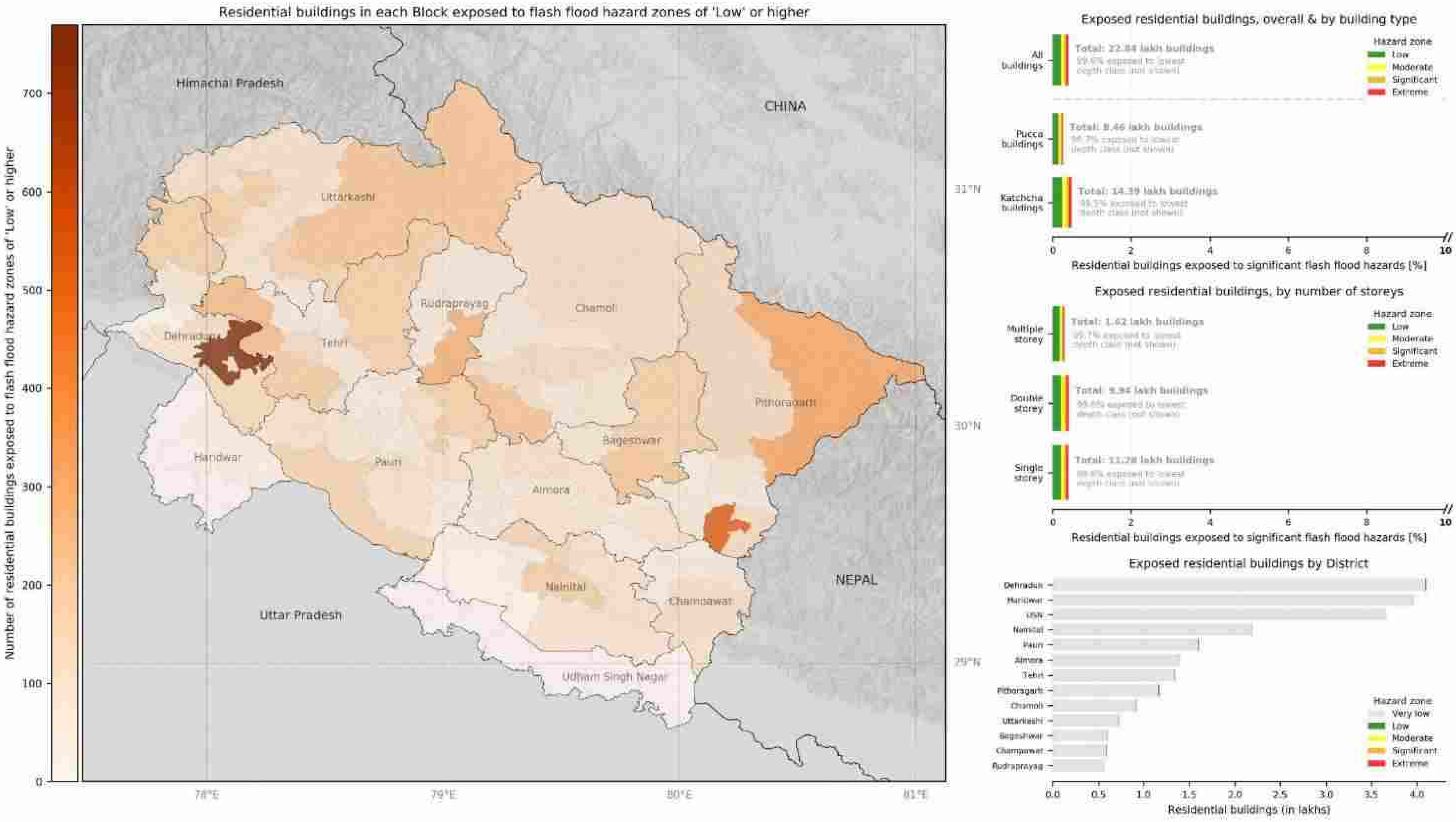

Figure 3.80: Visual summary of residential buildings exposed to flash flood hazard zones with a 100 year return period

3.4.6 Critical building exposure to floods (fluvial and flash)

Figure 3.81 shows the exposure of critical buildings to flood depths with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of health facilities, educational institutions, fire/police stations and other government buildings.

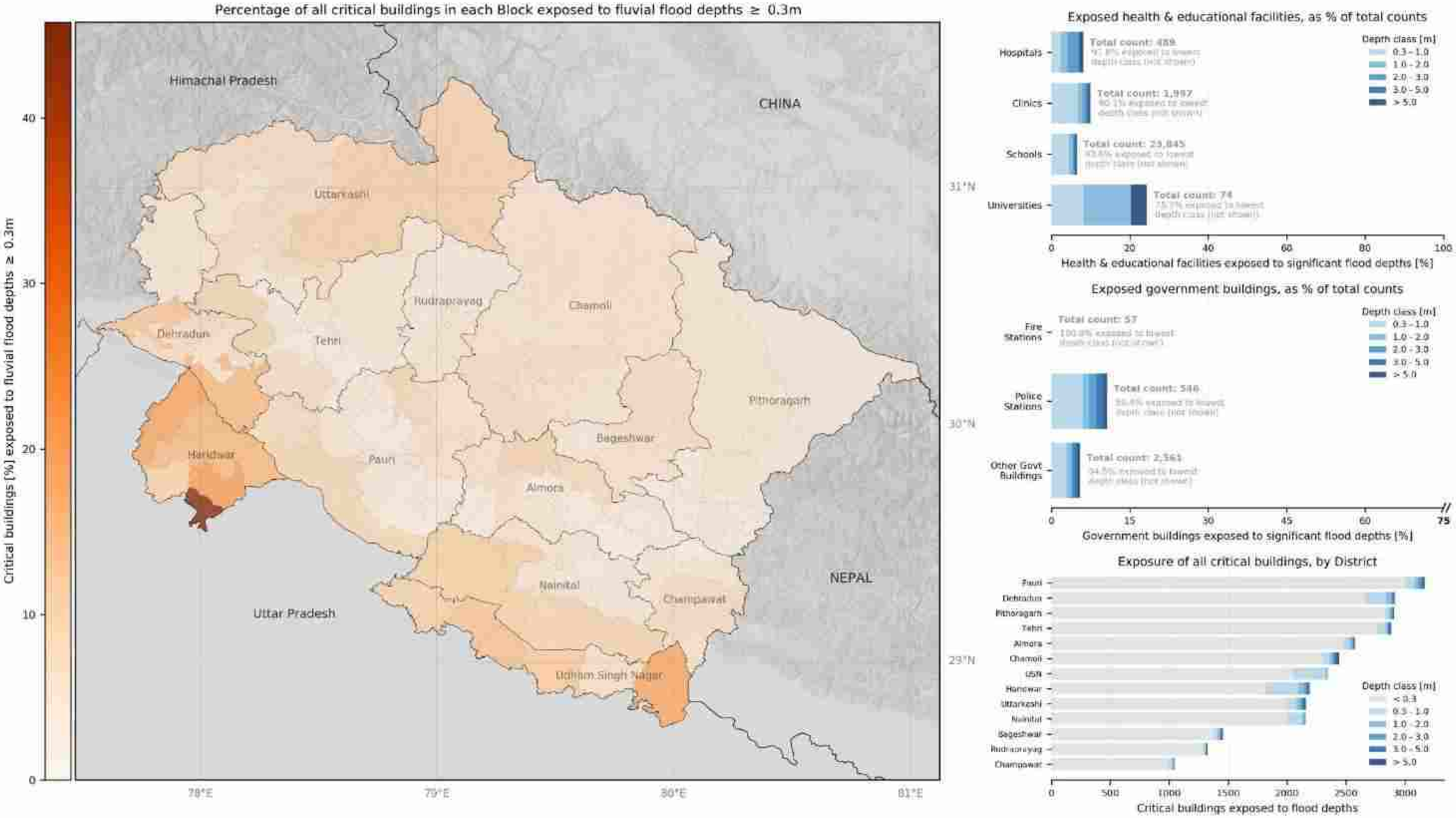

Figure 3.81: Visual summary of critical buildings exposed to flood depths with a 100 year return period

Figure 3.82 shows the exposure of critical buildings to flash flood hazards with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of health facilities, educational institutions, fire/police stations and other government buildings.

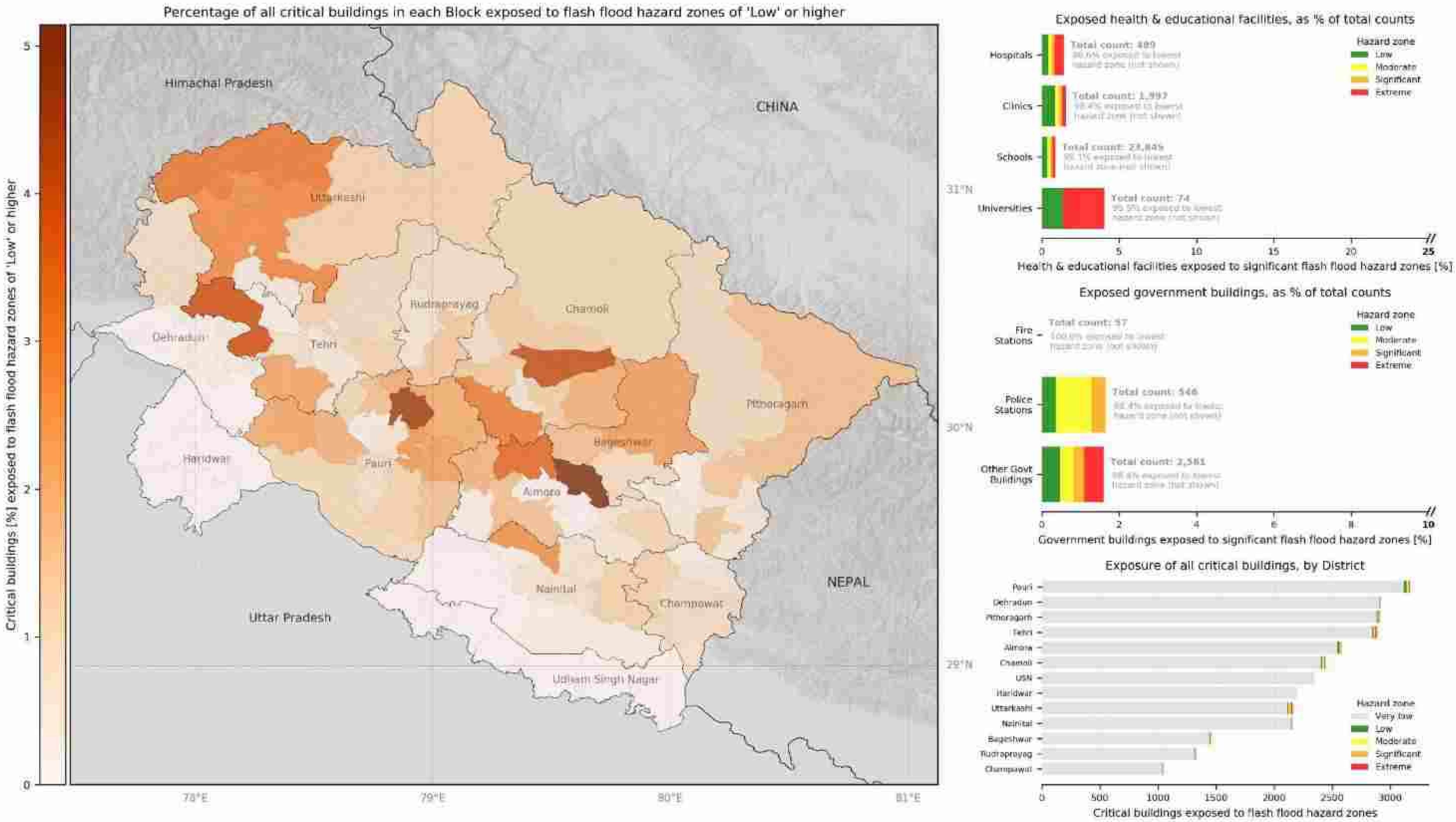

Figure 3.82: Visual summary of critical buildings exposed to flash flood hazard zones with a 100 year return period

3.4.7 Transportation infrastructure exposure to floods (fluvial and flash)

Figure 3.83 shows the exposure of transportation infrastructure to flood depths with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of road, rail and air infrastructure.

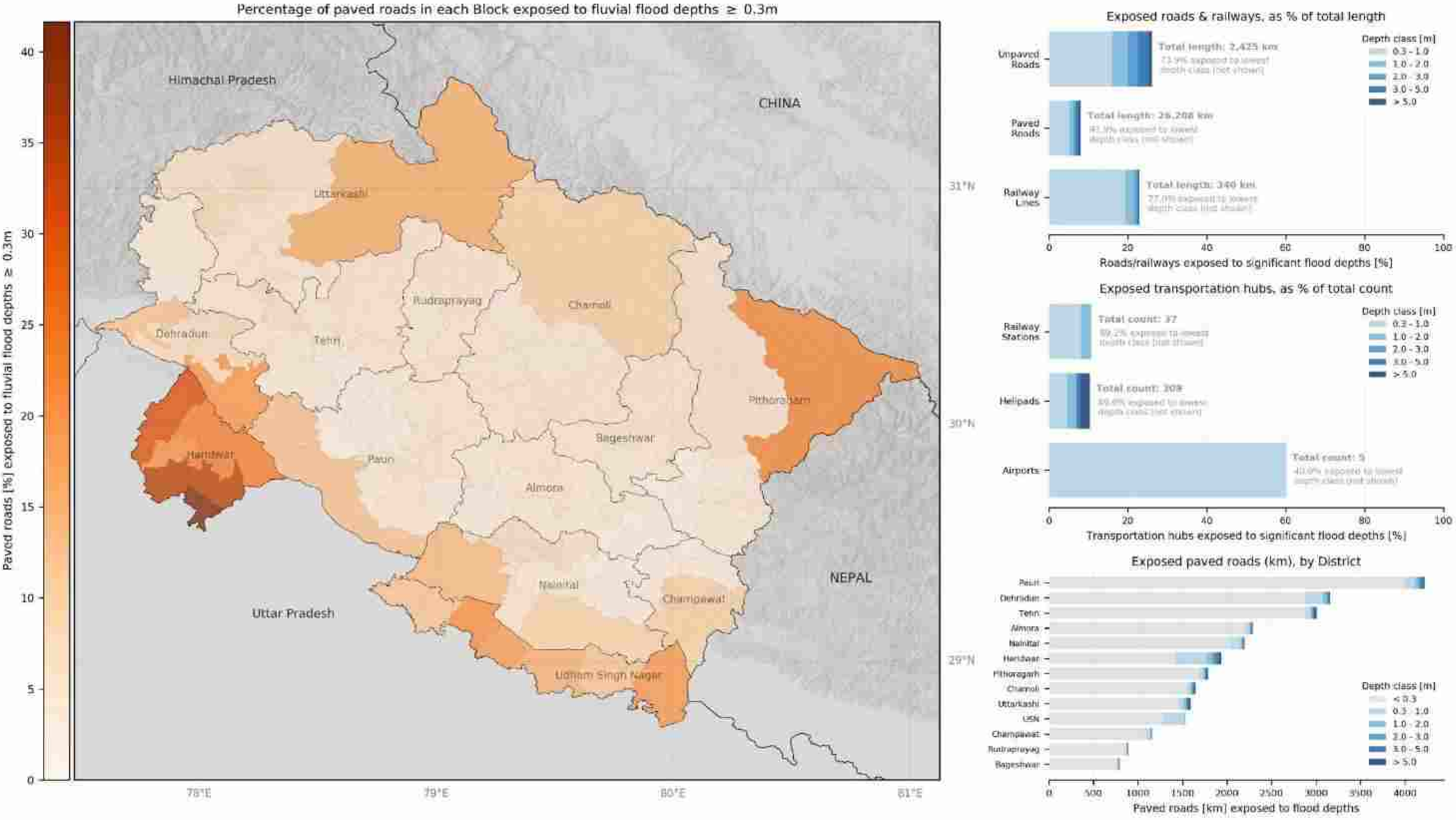

Figure 3.83: Visual summary of transportation infrastructure exposed to flood depths with a 100 year return period

Figure 3.84 shows the exposure of transportation infrastructure to flash flood hazards with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of road, rail and air infrastructure.

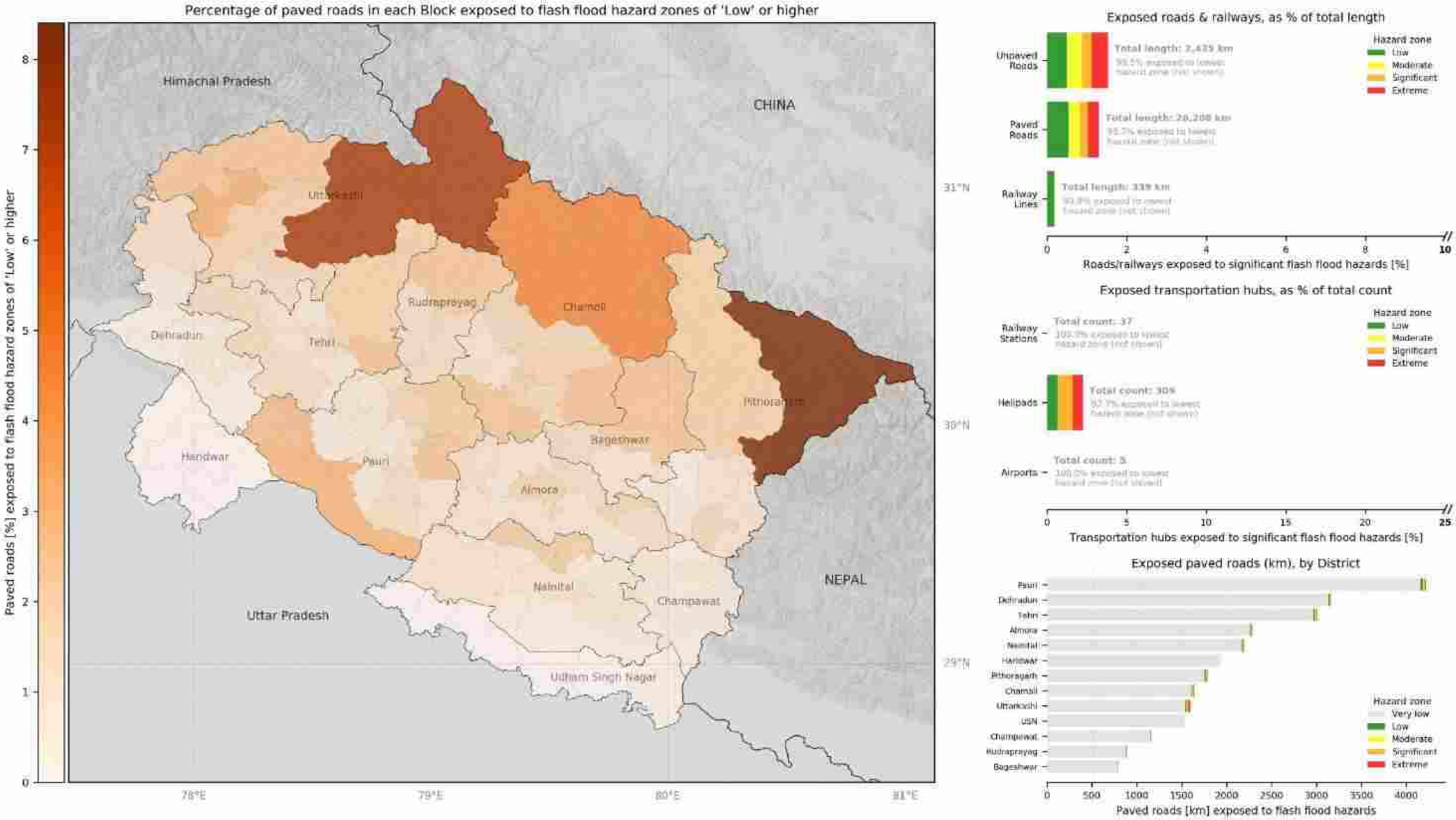

Figure 3.84: Visual summary of transportation infrastructure exposed to flash flood hazards zones with a 100 year return period

3.4.8 Power infrastructure exposure to floods (fluvial and flash)

Figure 3.85 shows the exposure of power infrastructure to flood depths with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of substations (transmission and distribution) and hydropower stations.

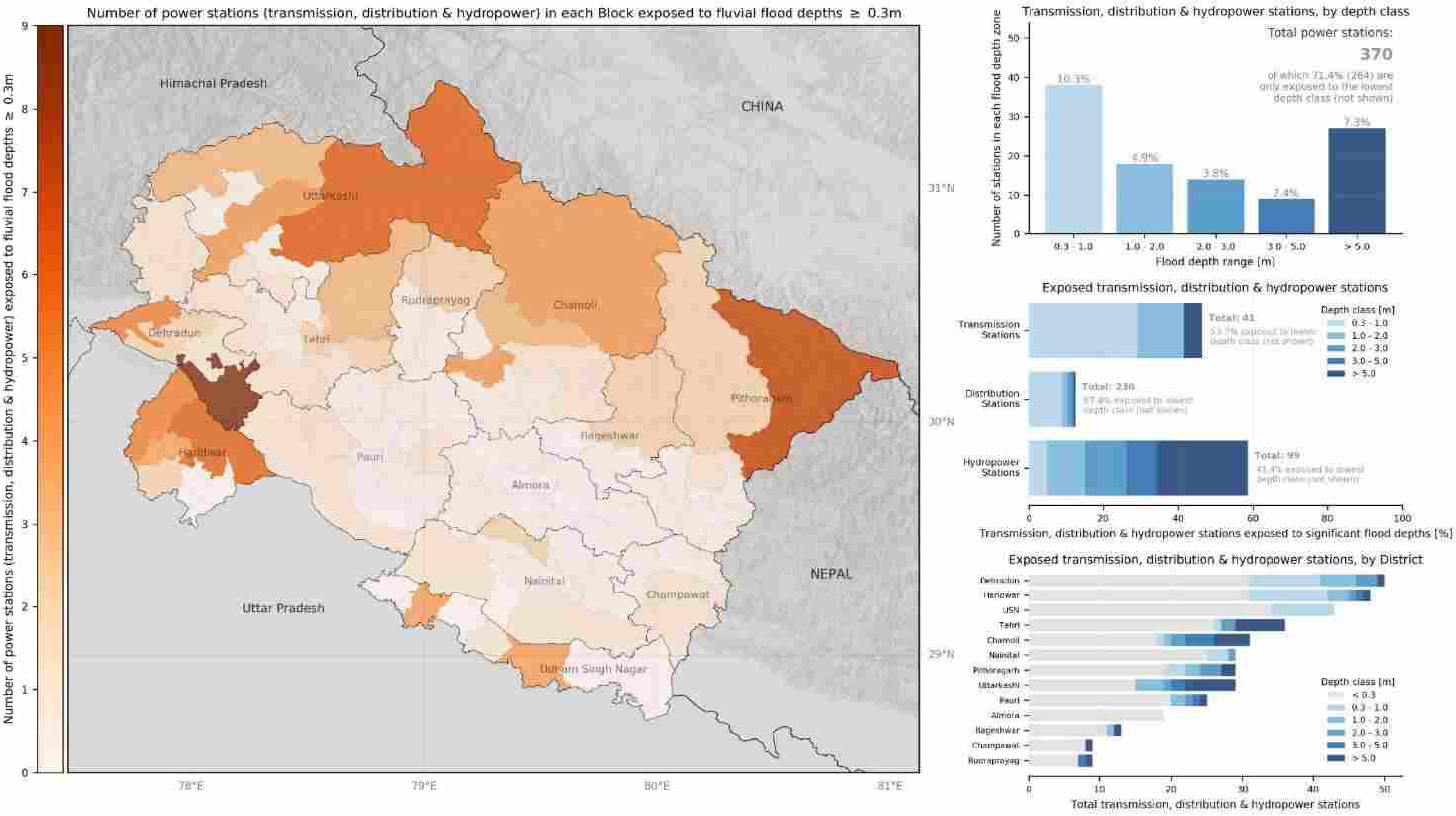

Figure 3.85: Visual summary of power infrastructure exposed to flood depths with a 100 year return period

Figure 3.86 shows the exposure of power infrastructure to flash flood hazards with a return period of 100 years. As illustrated in the plots, this portfolio is comprised of substations (transmission and distribution) and hydropower stations.

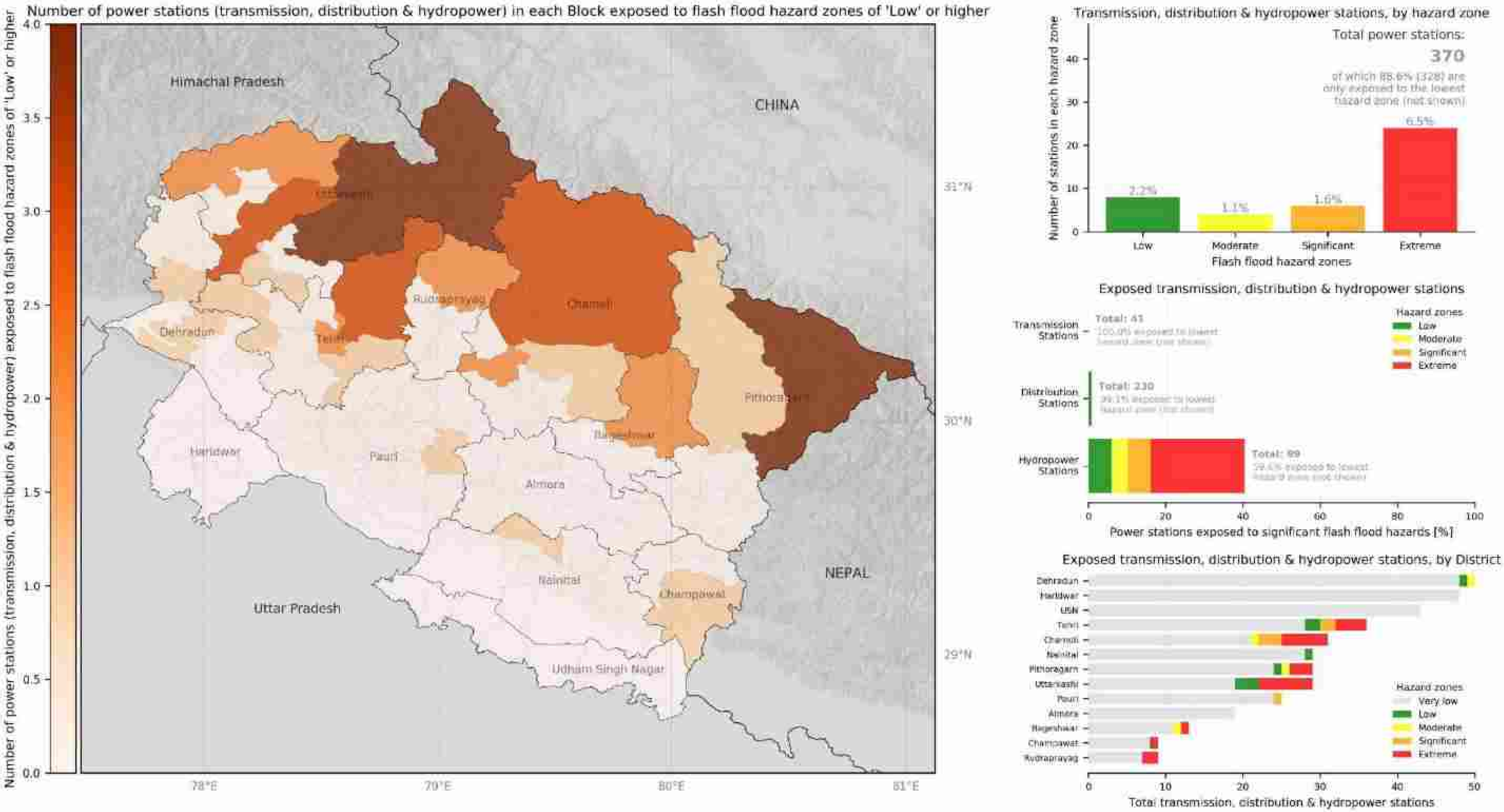

Figure 3.86: Visual summary of power infrastructure exposed to flash flood hazard zones with a 100 year return period

3.4.9 Economic sector exposure to floods (fluvial and flash)

Figure 3.87 shows the exposure of agriculture to flood depths with a return period of 100 years.

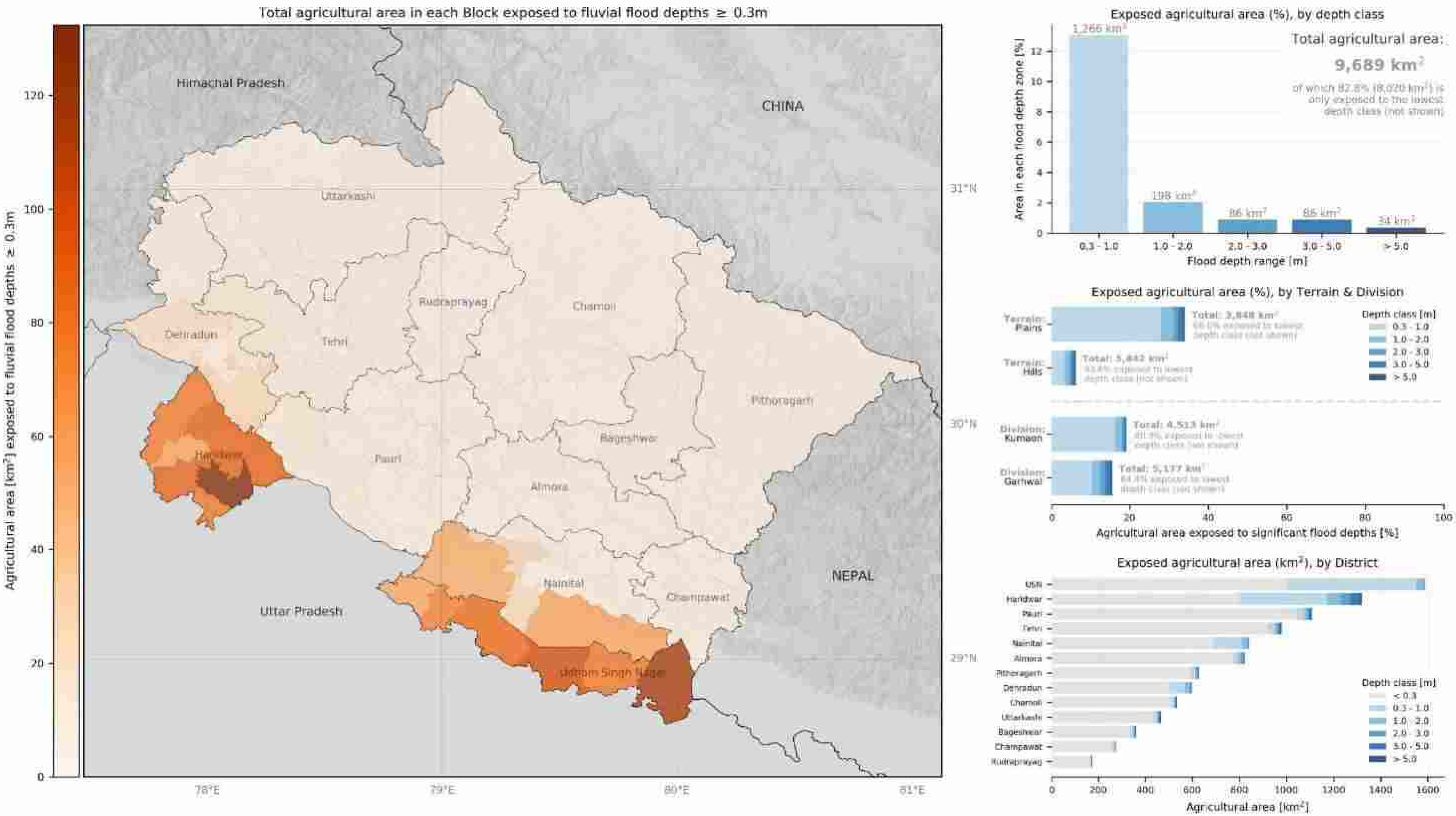

Figure 3.87: Visual summary of agriculture exposed to flood depths with a 100 year return period

Figure 3.88 shows the exposure of agriculture to flash flood hazards with a return period of 100 years.

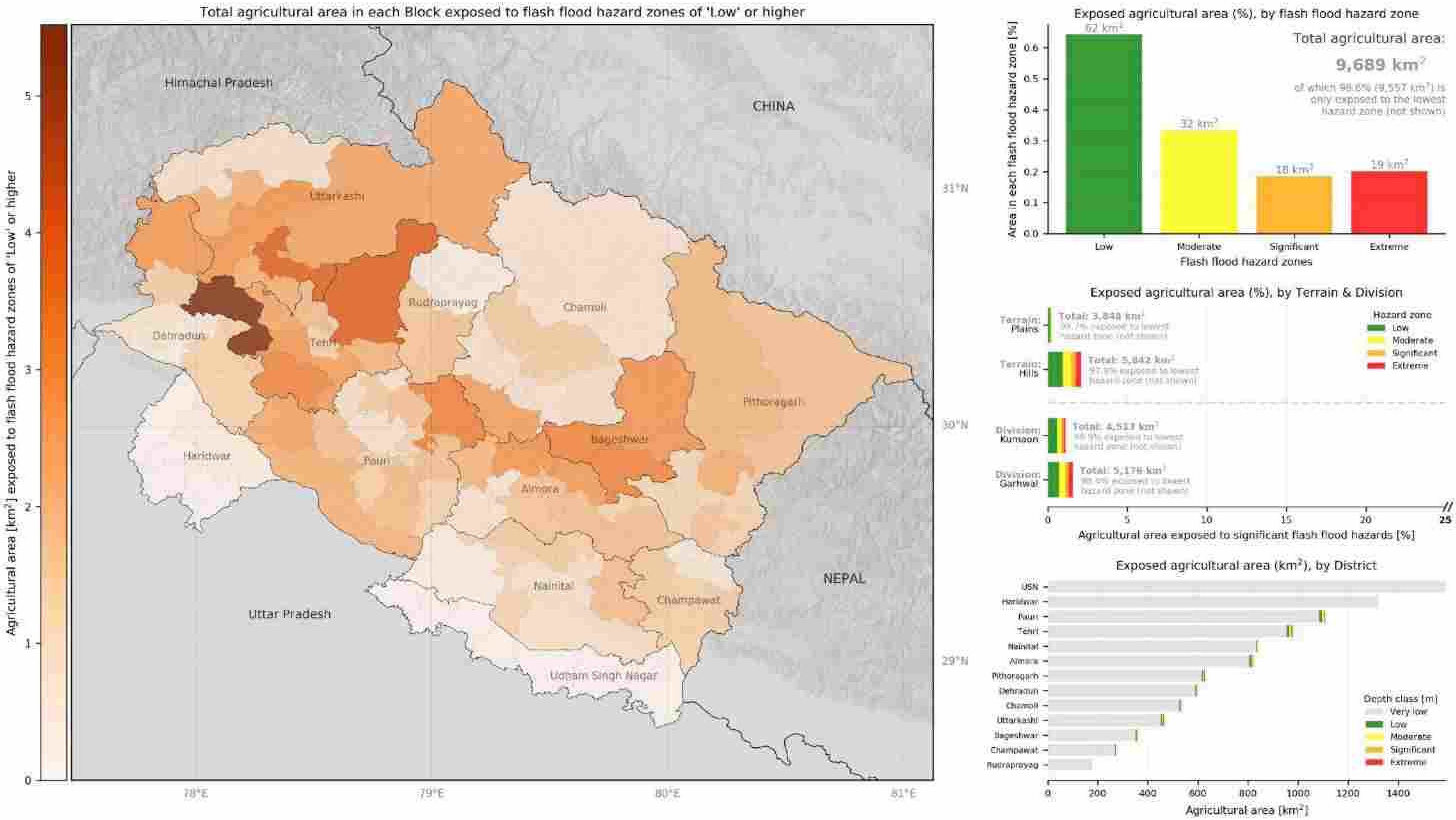

Figure 3.88: Visual summary of agriculture exposed to flash flood hazard zones with a 100 year return period

Figure 3.89 shows the exposure of horticulture (which includes equipment and other forms of capital investment) to flood depths with a return period of 100 years.

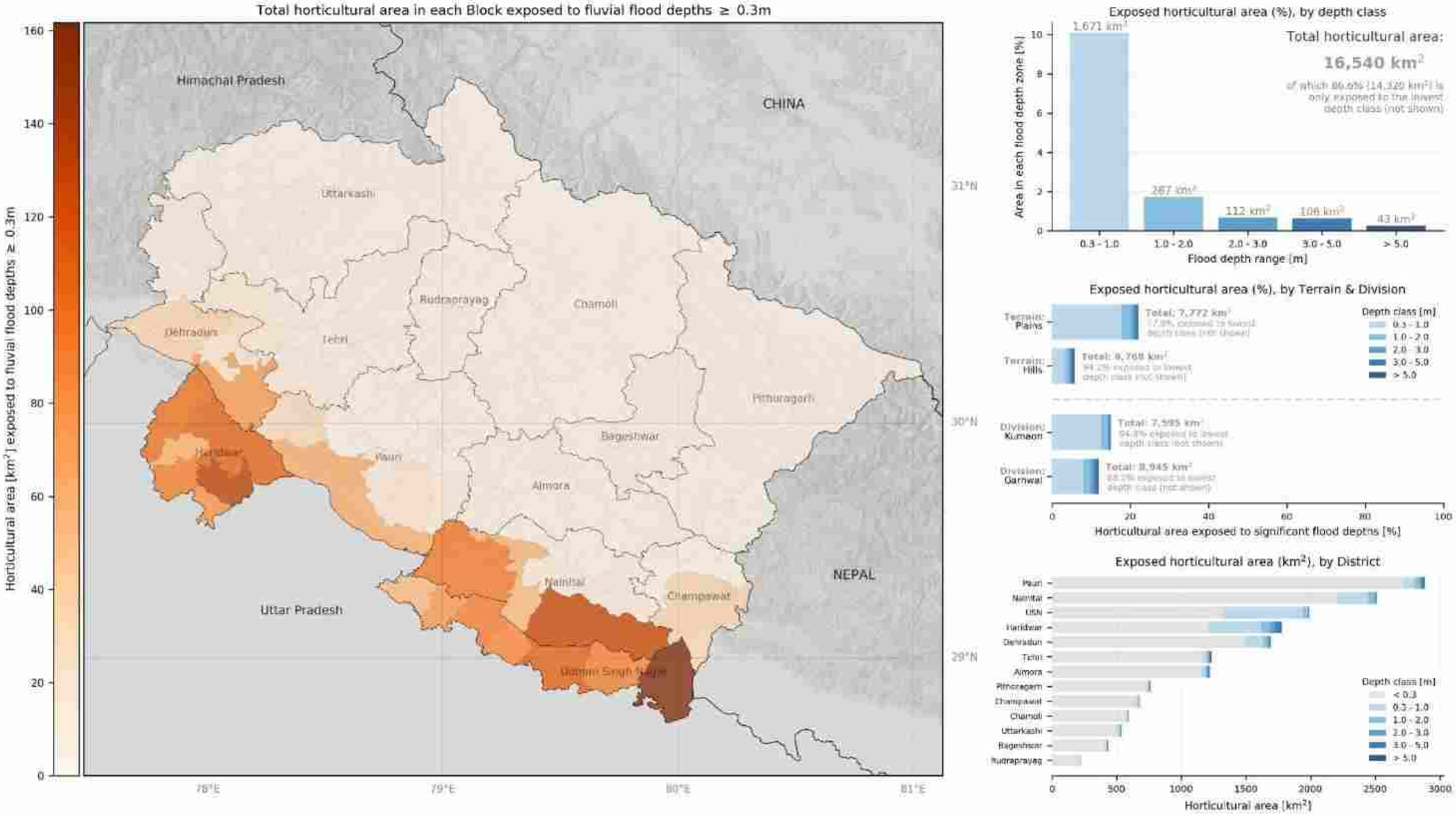

Figure 3.89: Visual summary of horticulture exposed to flood depths with a 100 year return period

Figure 3.90 shows the exposure of horticulture (which includes equipment and other forms of capital investment) to flash flood hazards with a return period of 100 years.

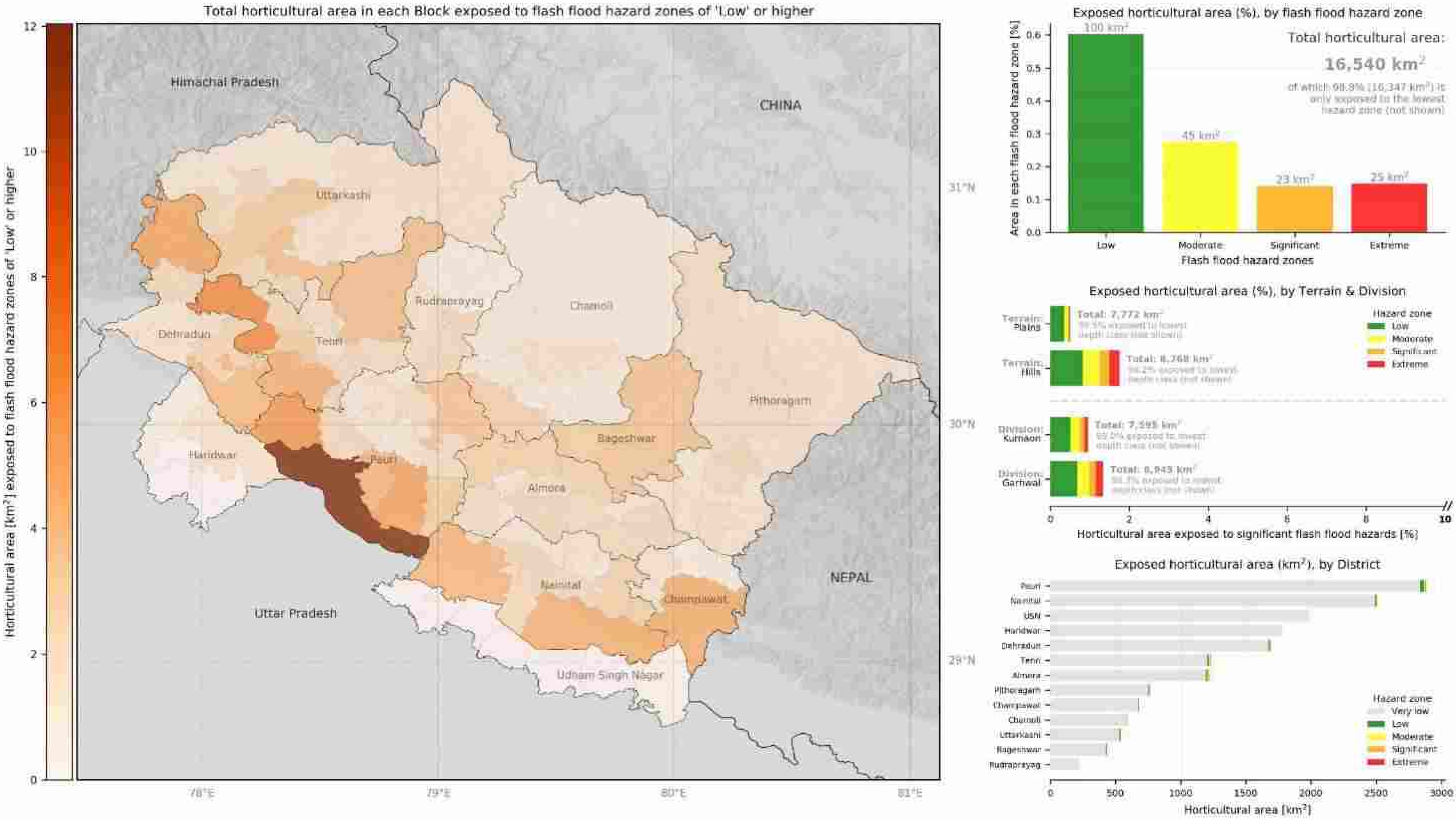

Figure 3.90: Visual summary of horticulture exposed to flash flood hazard zones with a 100 year return period

Figure 3.91 shows the exposure of industry, commerce and mining to flood depths with a return period of 100 years.

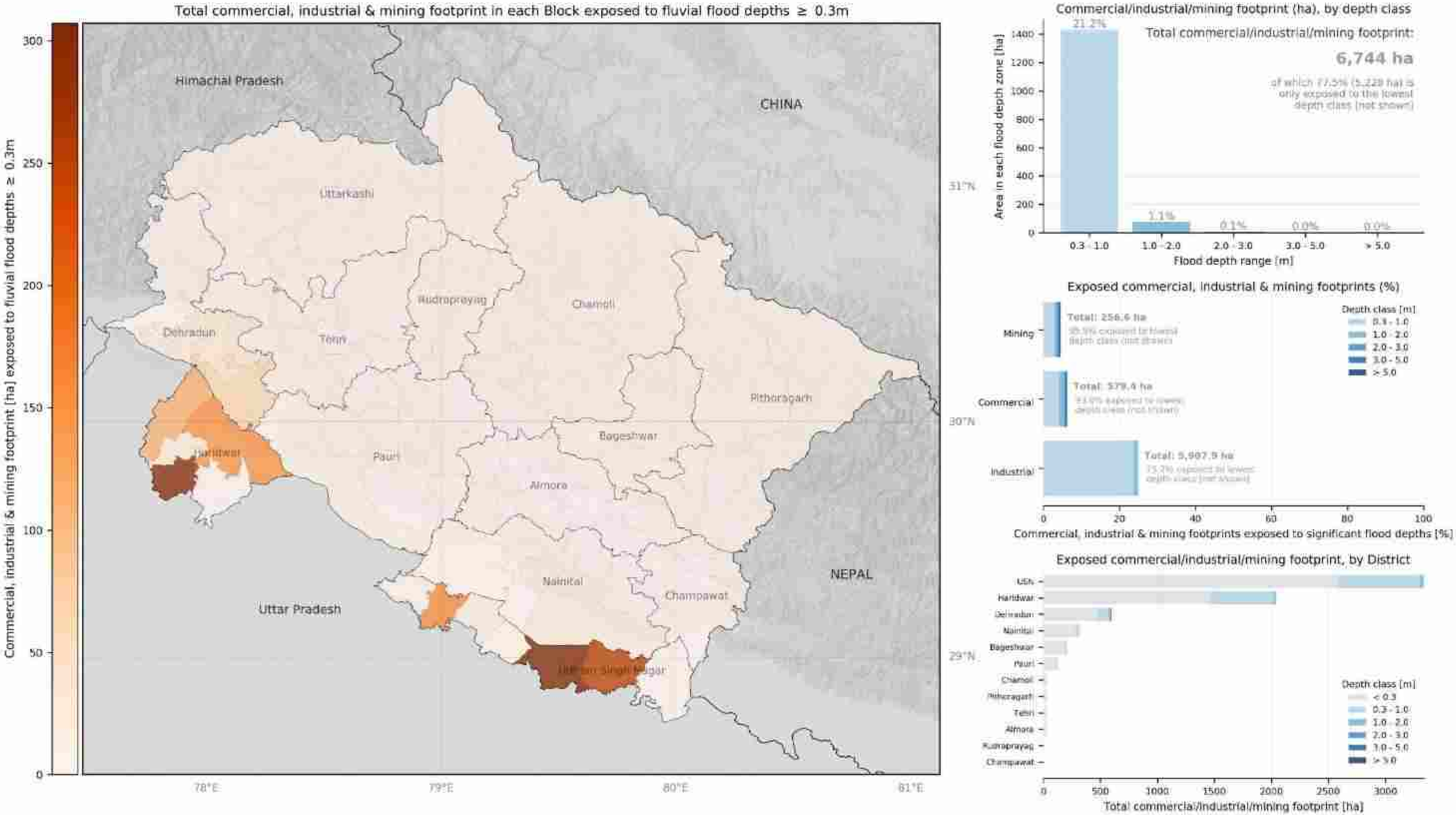

Figure 3.91: Visual summary of industry, commerce and mining exposed to flood depths with a 100 year return period

Figure 3.92 shows the exposure of industry, commerce and mining to flash flood hazards with a return period of 100 years.

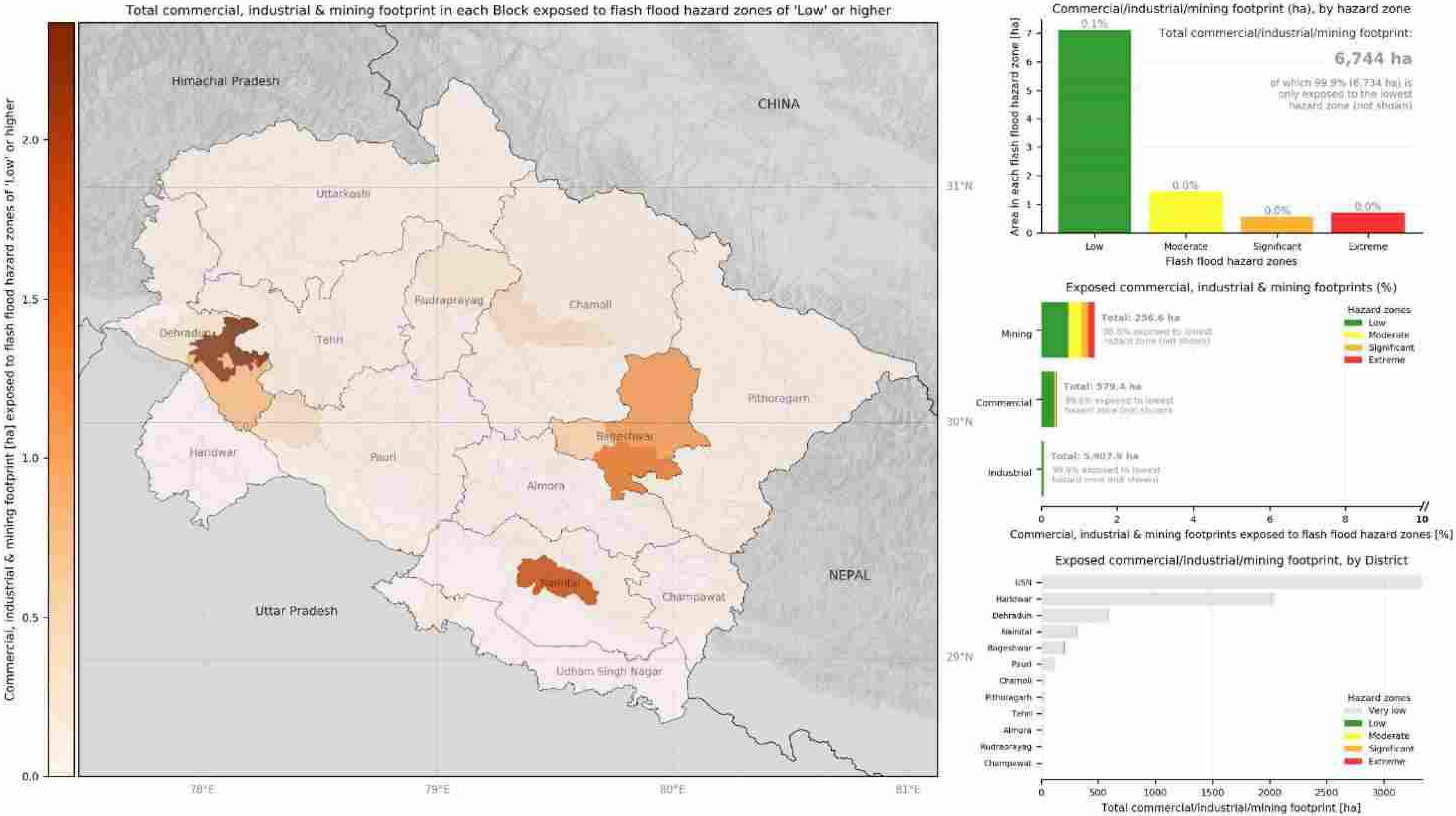

Figure 3.92: Visual summary of industry, commerce and mining exposed to flash flood hazard zones with a 100 year return period

Figure 3.93 shows the exposure of potential tourism revenue to flood depths with a return period of 100 years. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values).

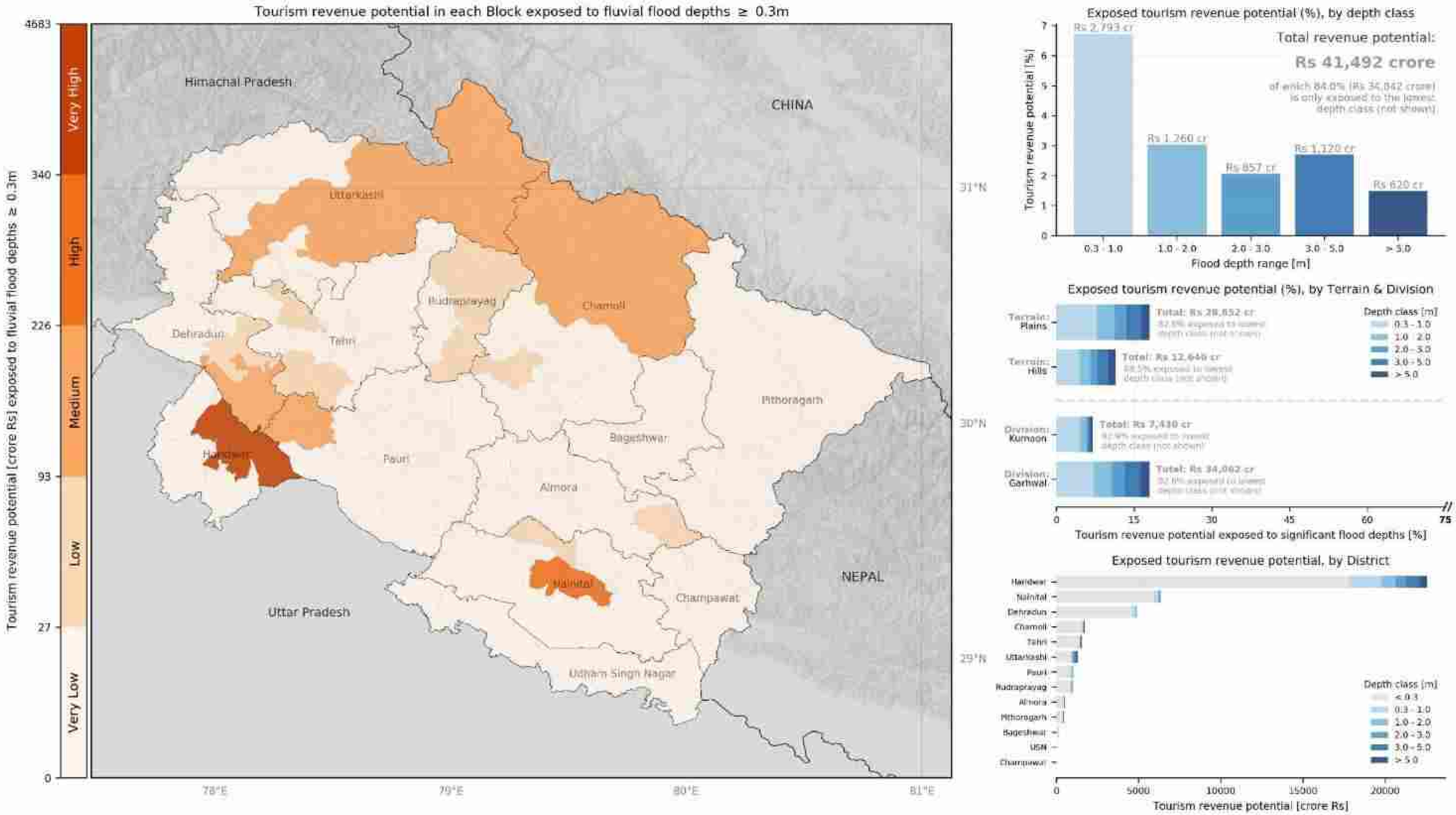

Figure 3.93: Visual summary of tourism revenue potential exposed to flood depths with a 100 year return period

Figure 3.94 shows the exposure of potential tourism revenue to flash flood hazards with a return period of 100 years. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values).

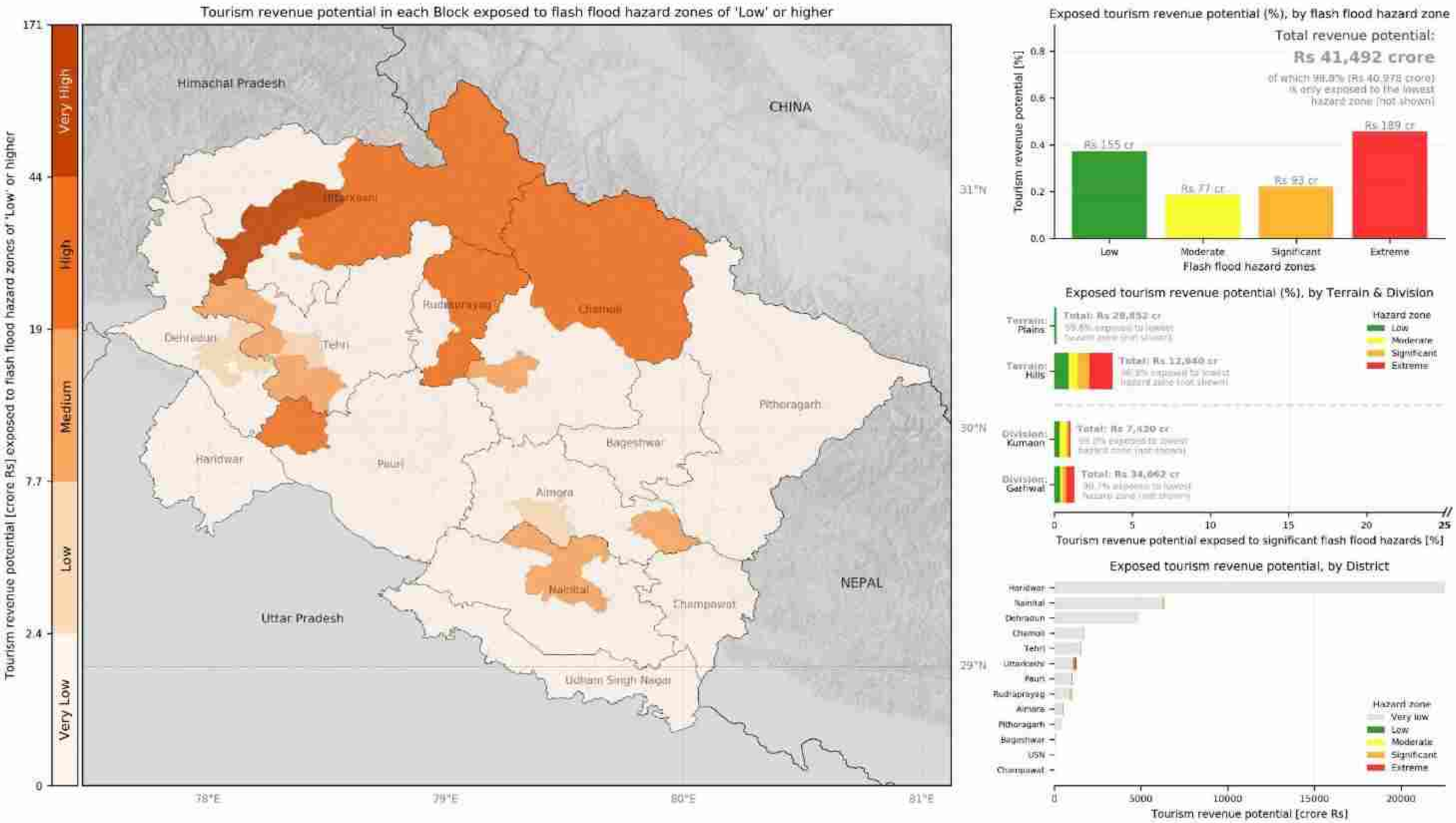

Figure 3.94: Visual summary of tourism revenue potential exposed to flash flood hazard zones with a 100 year return period

3.4	State Floods

Loss Profile (Fluvial Floods Only)

The Average Annual Loss (AAL) of economic value in the State due to fluvial floods is approximately Rs 66 crores. Figure 3.95 shows how this total is distributed between the various portfolios and their individual components. Note that buildings and people have been assumed to be protected from higher-frequency events (up to the 100 year event in urban areas and the 25 year event in rural areas), based on observations made during field trips around the state. This does not apply to agriculture, horticulture, roads or railways, which are considered unprotected.

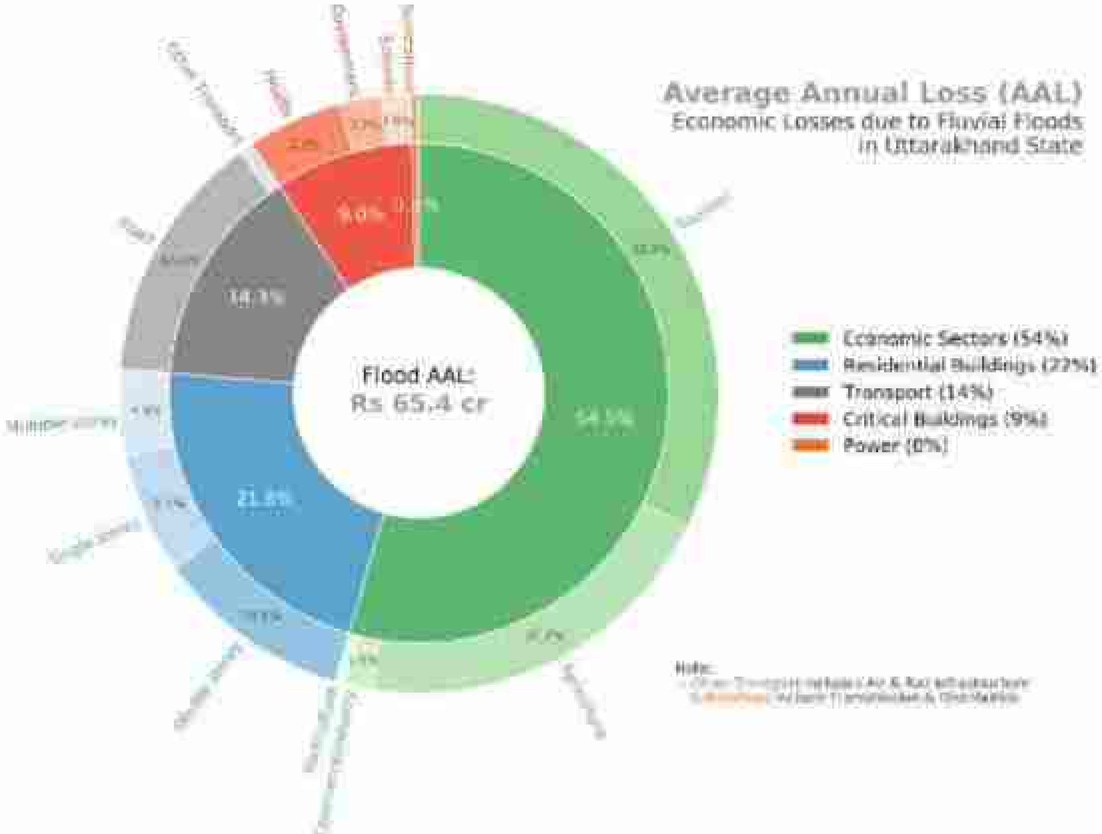

Figure 3.95: Distribution of Economic AAL due to fluvial floods, by portfolio and sub-portfolio

In Figure 3.96, the total AAL of economic value due to fluvial floods in each district of the state is displayed, as well as the distribution of each district's total AAL by portfolio.

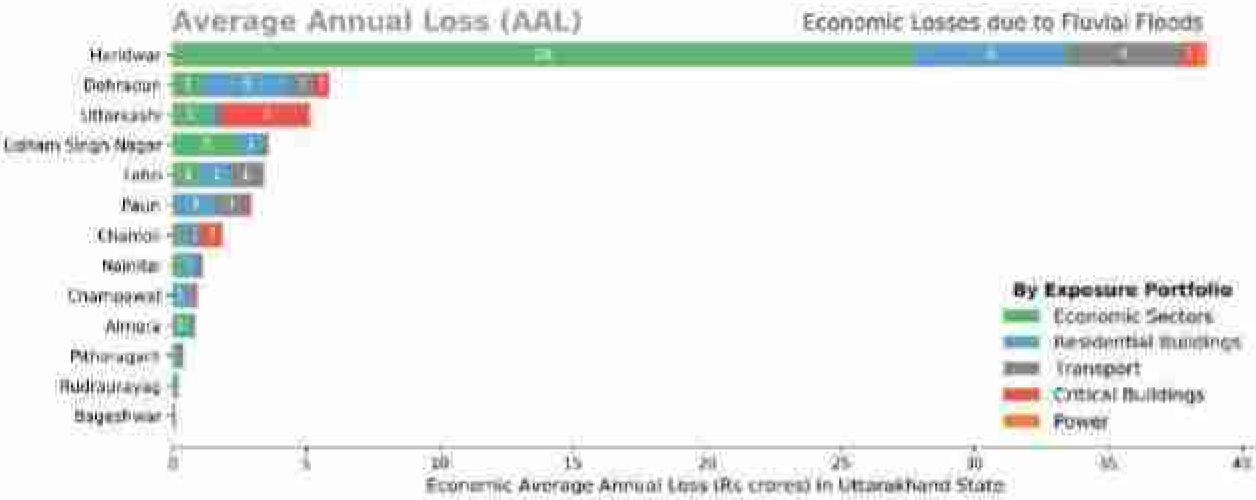

Figure 3.96: Distribution of Economic AAL due to fluvial floods, by portfolio and district

The economic losses presented above include both direct losses (those incurred at the time of the disaster, in terms of damaged assets that have to be repaired or replaced) and indirect losses (the loss of likely future income due to the disruption of revenue streams such as industrial production or tourism activities).

In the case of the latter, assumptions must be made as to the maximum period over which revenue streams may be impacted by a given disaster (with actual losses scaled proportionately according to the calculated damage percentage). Table 3.4 summarises these assumptions for each economic portfolio/sub-portfolio included in the risk assessment, as well as providing a general overview of the direct and indirect losses considered. It is noted that cascading indirect losses (such as industrial losses due to disruption of power infrastructure) are not within the scope of the current assessment and therefore not accounted for in the loss estimates.

Table 3.4: Overview of direct and indirect losses accounted for, including maximum disruption periods for indirect losses

Portfolio	Sub-portfolios	Direct losses	Indirect losses	Max disruption
Residential Buildings	Katchcha	Replacement cost	None	NA
	Pucca			
Critical Buildings	Health, Schools, Government	Replacement cost	None	NA
Transport Infrastructure	Road, Rail, Air	Replacement cost	None	NA
Power Infrastructure	Power substations	Replacement cost	None	NA
	Hydropower stations	Replacement cost	Loss of electricity revenue	1 year
Economic Sectors	Agriculture, Horticulture	Replacement cost (capital investment)	Loss of future yields	1 year
	Industry	Replacement cost (capital investment)	Loss of future production revenue	1 year
	Commerce	None	Loss of manufacturing & services revenue	1 year
	Mining	None	Loss of production revenue	1 year
	Tourism	None	Loss of tourism revenue	18 months (remote) 12 months (moderate) 6 months (accessible)

Figure 3.97 illustrates the distribution of direct and indirect losses within the state's overall economic AAL due to fluvial floods.

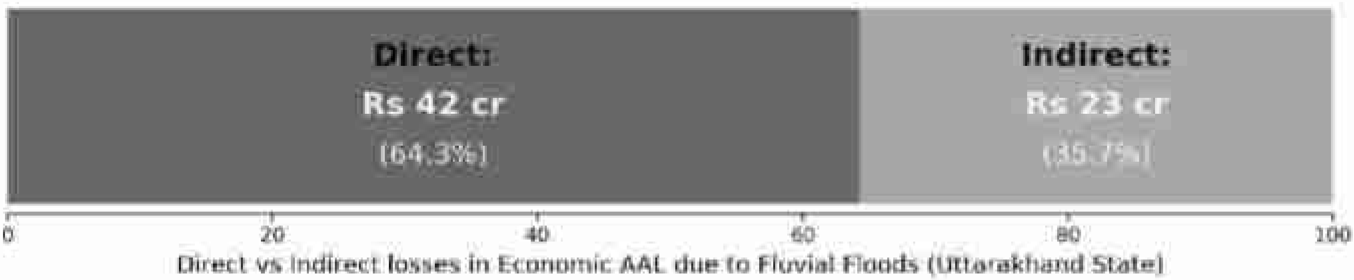

Figure 3.97: Distribution between direct and indirect losses in the State's Economic AAL, due to fluvial floods

Figure 3.98 presents the ranking of all Districts and Blocks within the State, in terms of their total Average Annual Loss (AAL) of economic assets, as a result of both direct and indirect losses caused by fluvial floods. Note that only those blocks impacted by the major rivers modelled for this study are shown here.

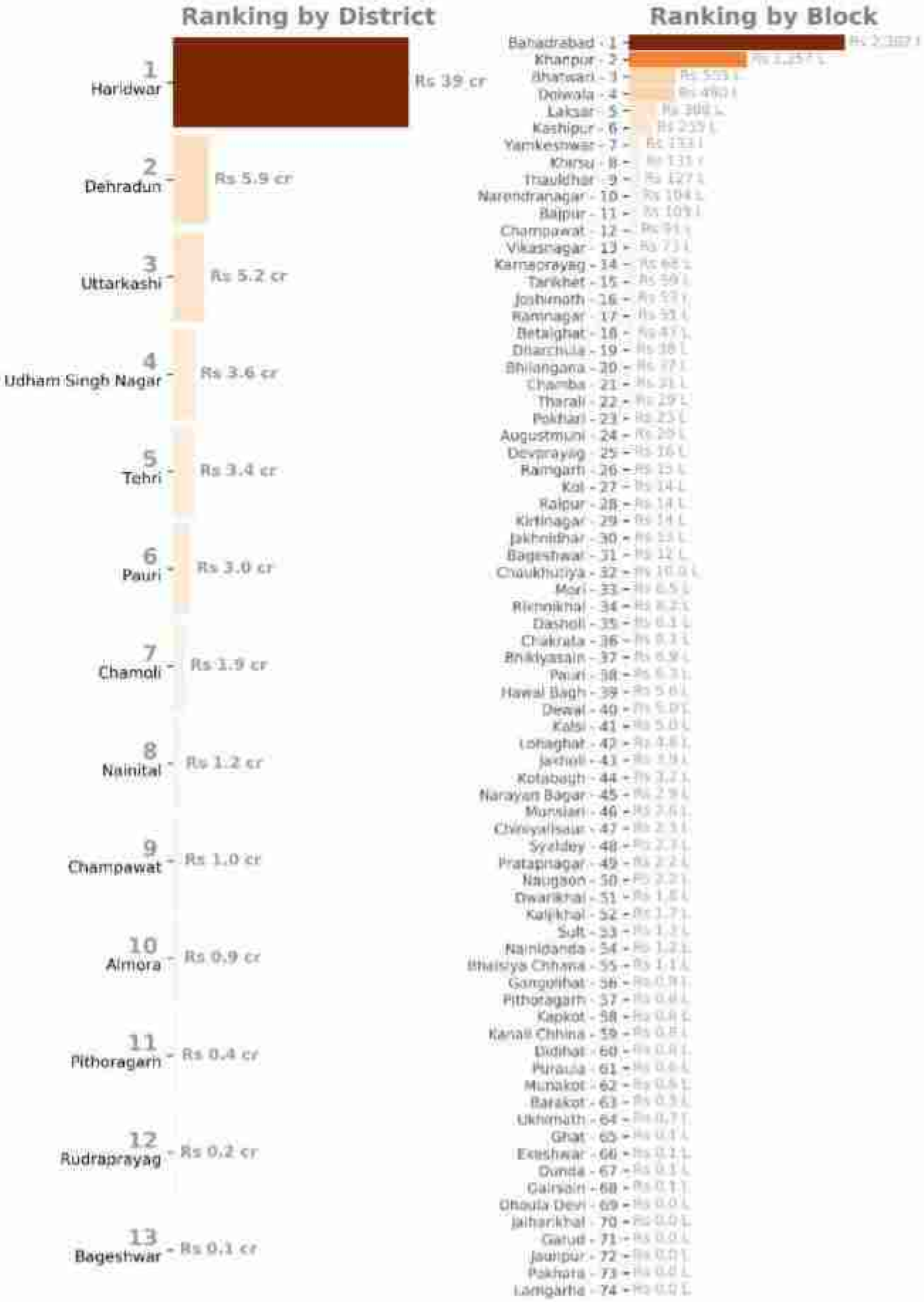

Figure 3.98: Ranking of all Districts and Blocks in the State, based on Average Annual Loss (Economic) due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.99 presents the overall PML curve for all economic assets modelled in the state, for two sets of assumptions: standard protection (built exposure protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

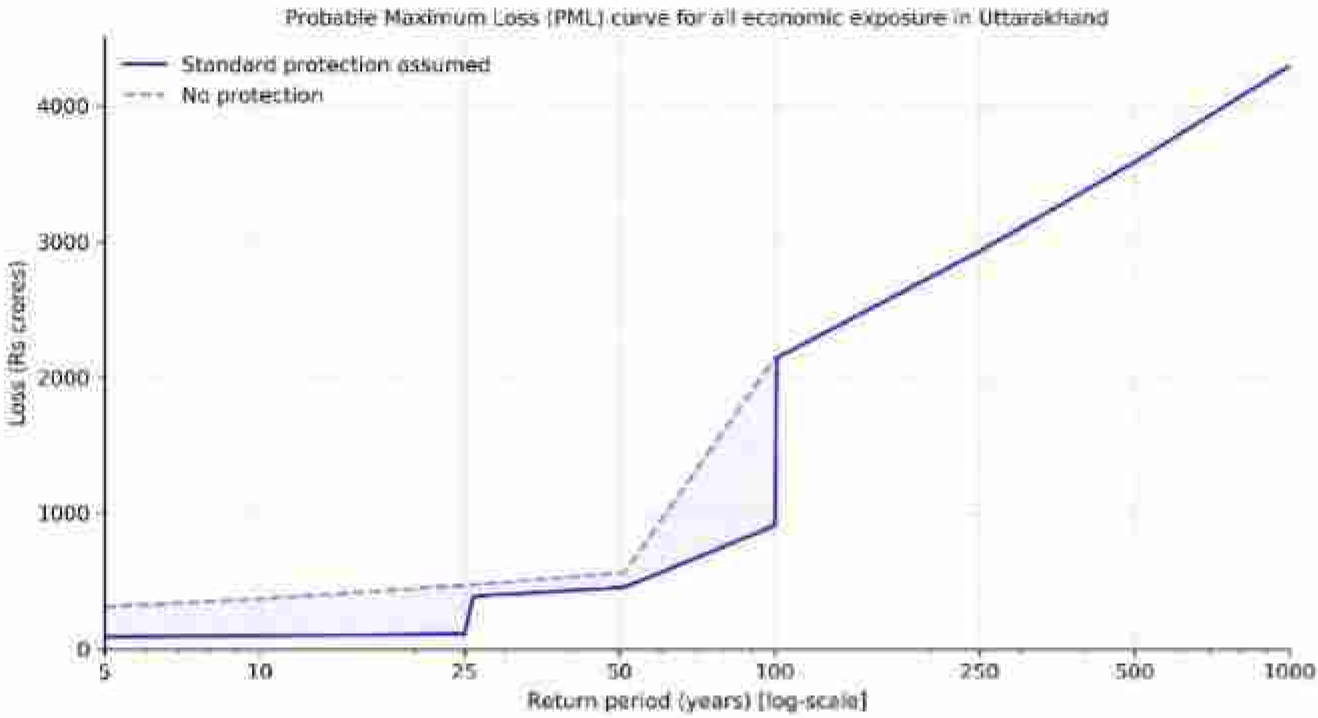

Figure 3.99: Probable Maximum Loss (PML) curve for all economic assets in Uttarakhand due to fluvial floods

Figure 3.100 presents individual PML curves (based on the standard protection assumption described above) for each of the mapped economic portfolios in the state.

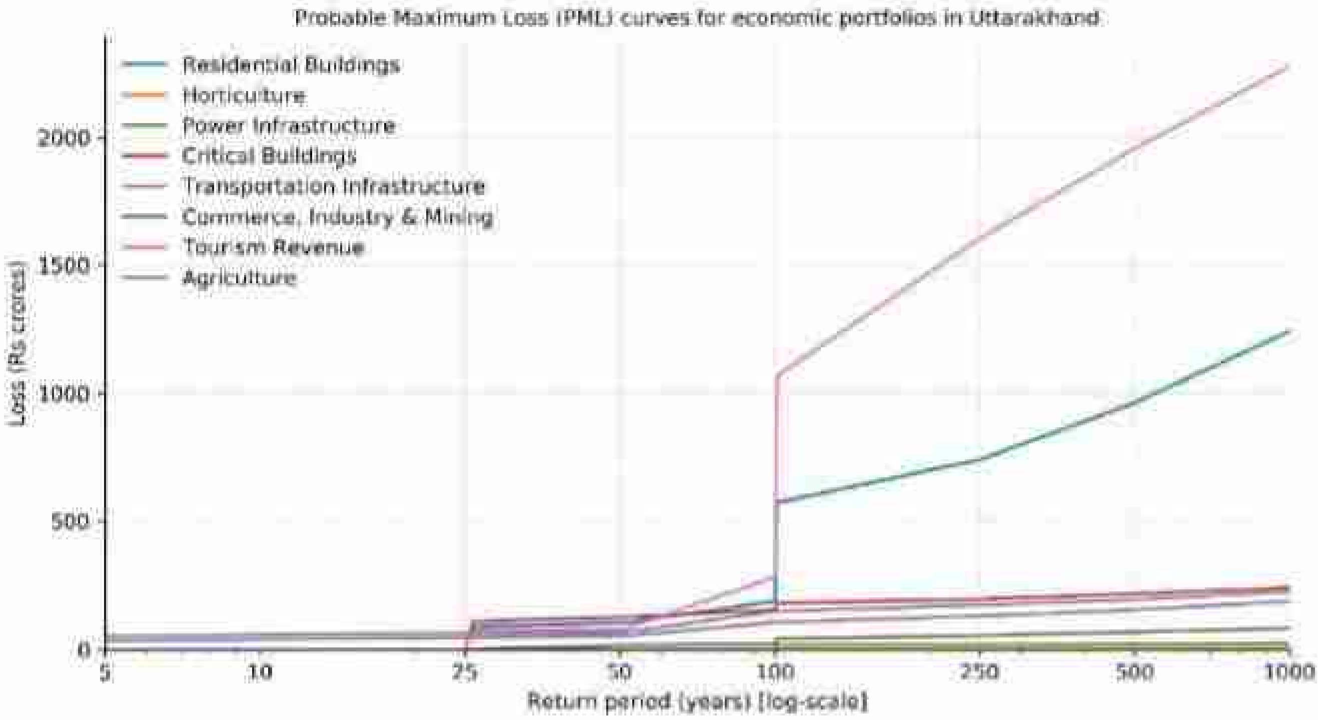

Figure 3.100: Probable Maximum Loss (PML) curve for each economic portfolio in Uttarakhand due to fluvial floods

As for human losses, the Average Annual Loss (AAL) in the State due to fluvial floods is estimated to be four (4) lives. Figure 3.101 summarises the distribution of this total, in terms of the residency of those killed (state residents or tourists), the time of the flood event, and the land use (Rural / Urban) of the area they were in at the time.

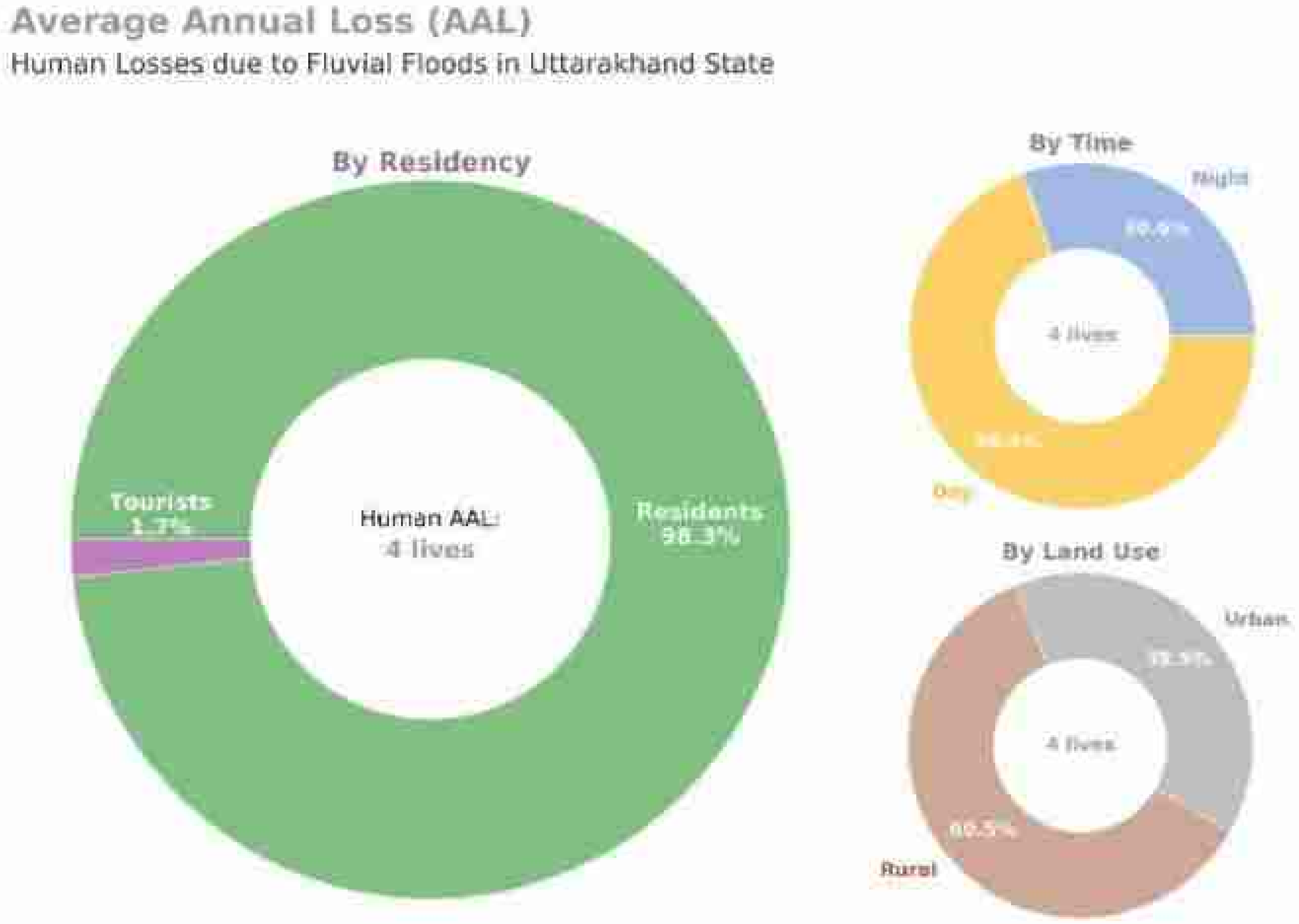

Figure 3.101: Average Annual Loss (AAL) of human lives, by residency, time of flood event and land use type

Figure 3.102 summarises the AAL of human lives in each of the State's districts, as well as the distribution of each district's AAL in terms of the residency of those affected (state residents or tourists).

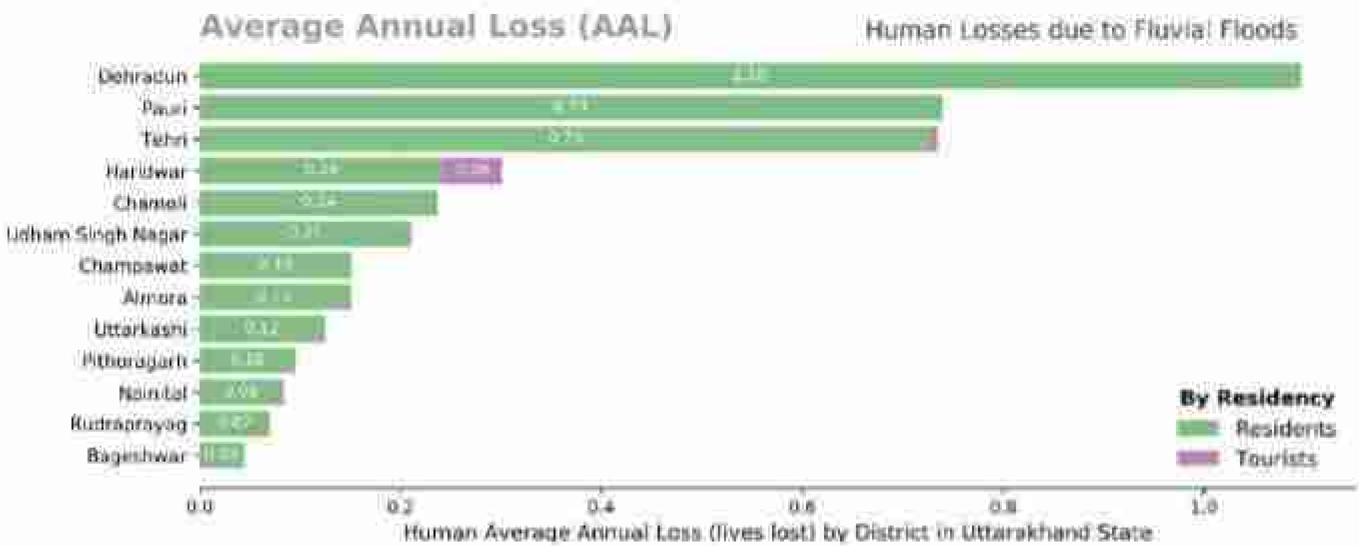

Figure 3.102: Average Annual Loss (AAL) of human lives, by district and residency (residents/tourists)

Figure 3.103 presents the ranking of all Districts and Blocks within the State, in terms of their total Average Annual Loss (AAL) of human lives, as a result of fluvial floods. Note that only those blocks impacted by the major rivers modelled for this study are shown here.

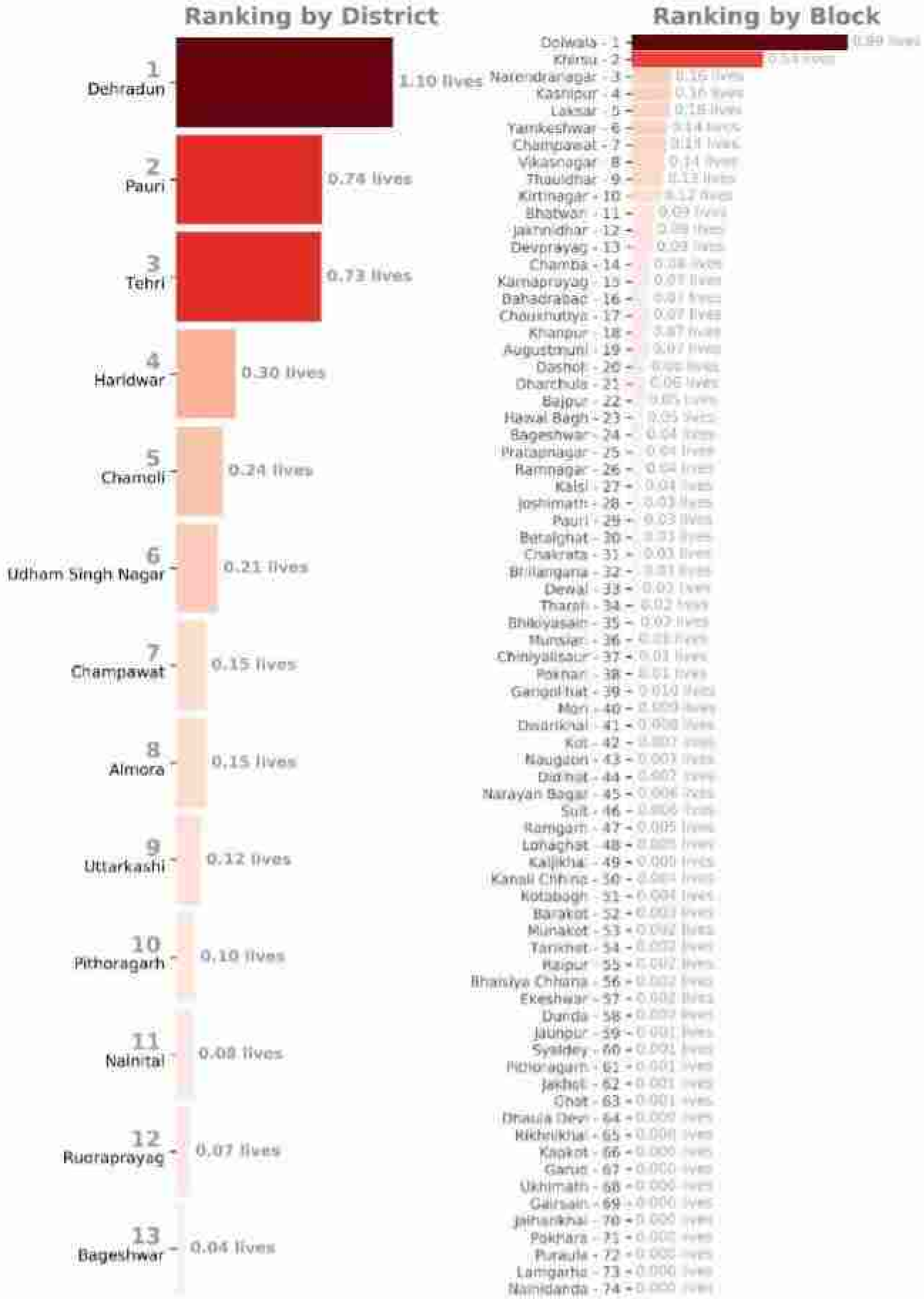

Figure 3.103: Ranking of all Districts and Blocks in the State, based on Average Annual Loss (Human) due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.104 presents the overall PML curve for all people (residents and tourists) in the state, for two sets of assumptions: standard protection (people protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

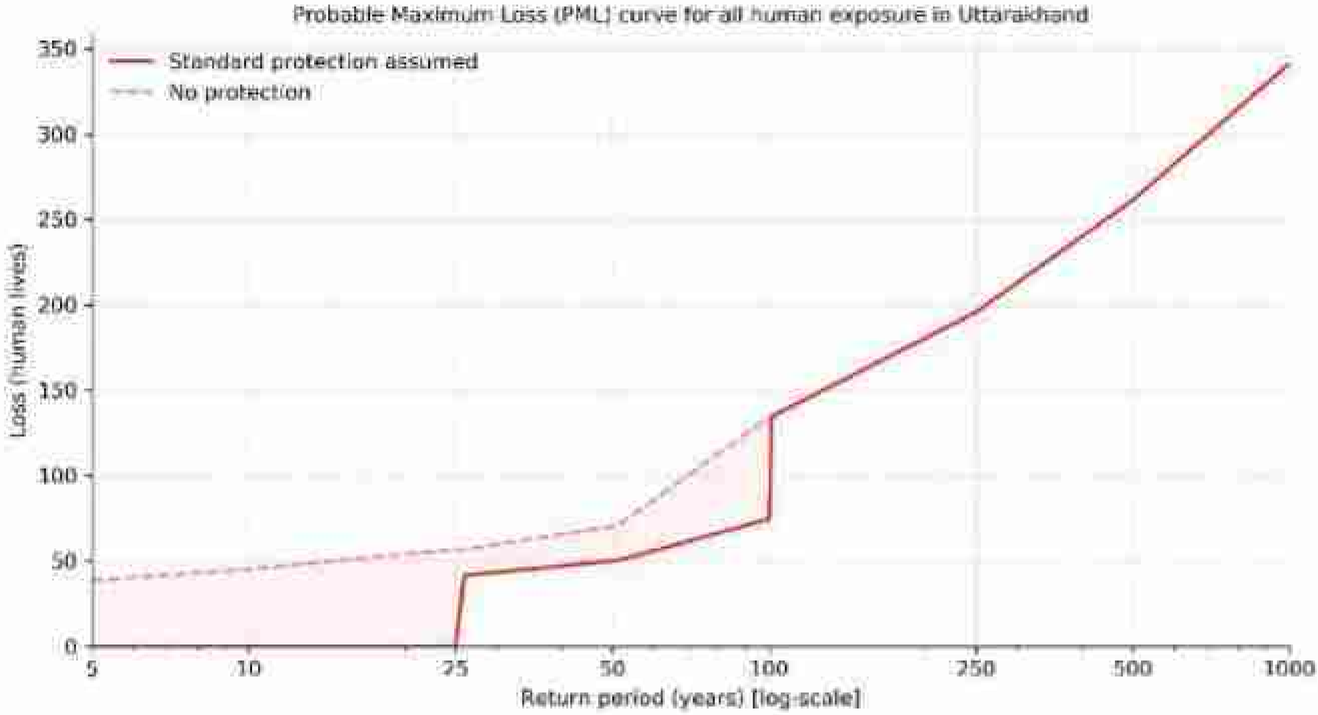

Figure 3.104: Probable Maximum Loss (PML) curve for human life in Uttarakhand due to fluvial floods

Figure 3.105 presents individual PML curves (based on the standard protection assumption described above) for each of the mapped human groups in the state (residents and tourists).

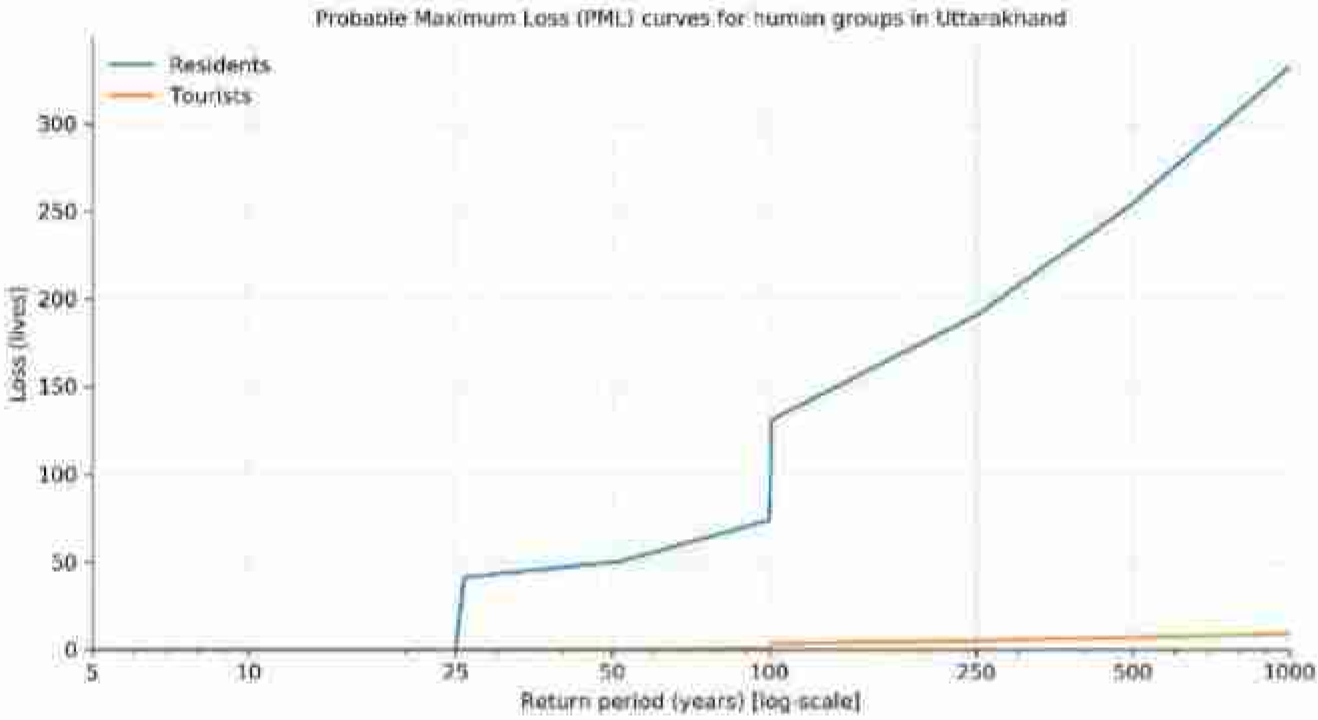

Figure 3.105: Probable Maximum Loss (PML) curve for each human group in Uttarakhand due to fluvial floods

The human AAL discussed so far provides an estimate of the likely loss of life directly attributable to fluvial floods (primarily resulting from drowning and the impact of flood-borne debris). However, there are likely to be longer-term morbidity impacts too, depending on the extent to which the affected area's capacity to respond to the disaster has been compromised. This will depend on factors such as:

- Size of displaced population to be housed in temporary camps (where disease outbreaks more likely)
- Likelihood of significant standing water near population (increases risk of vector-borne diseases)
- Capacity of local health facilities (those still functional post-disaster)
- Capacity of other government facilities to support response/recovery efforts
- Transport connectivity within the affected area (particularly road and air transport)
- Pre-existing socio-economic vulnerability of population in affected area
- Fraction of affected population made up of tourists (less local knowledge and thus more vulnerable)
- Risk of vector- and water-borne disease transmission due to ponded water after a flood

While detailed modelling to quantify this risk is not possible, a qualitative assessment has been performed, in order to evaluate the likely significance of morbidity in the state (overall and also in terms of the individual factors listed above) due to fluvial floods.

It should be clearly noted that this is a *relative* assessment only (each District is compared to all other Districts in the State, and likewise for Blocks) rather than being assessed against an external standard or reference. Thus it can be stated with some confidence that one District is at a higher morbidity risk than another, but the actual level of that risk remains unknown.

A map showing the overall fluvial flood-dependent morbidity risk class estimated for each Block (left) and each District (upper right) in Uttarakhand is presented in Figure 3.106, along with a histogram of the class distribution for blocks (lower right). Further details for each District and Block are available in the corresponding Atlas volume.

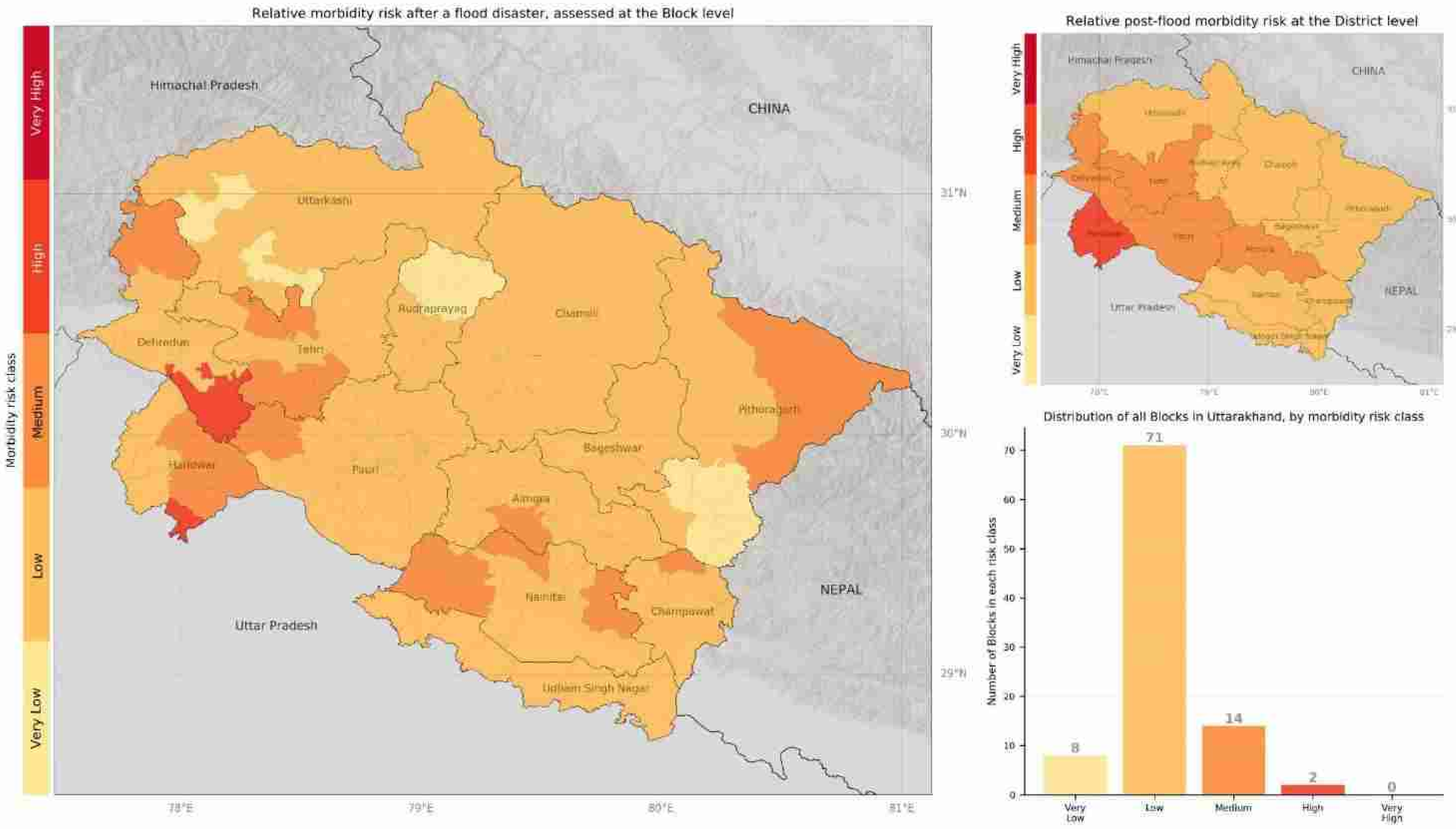

Figure 3.106: Overall fluvial flood-dependent morbidity risk classes estimated for all Blocks and Districts in Uttarakhand

3.4.10 Population losses due to floods (fluvial)

Figure 3.107 shows the Average Annual Loss (AAL) of human lives (state residents) due to fluvial flood hazards.

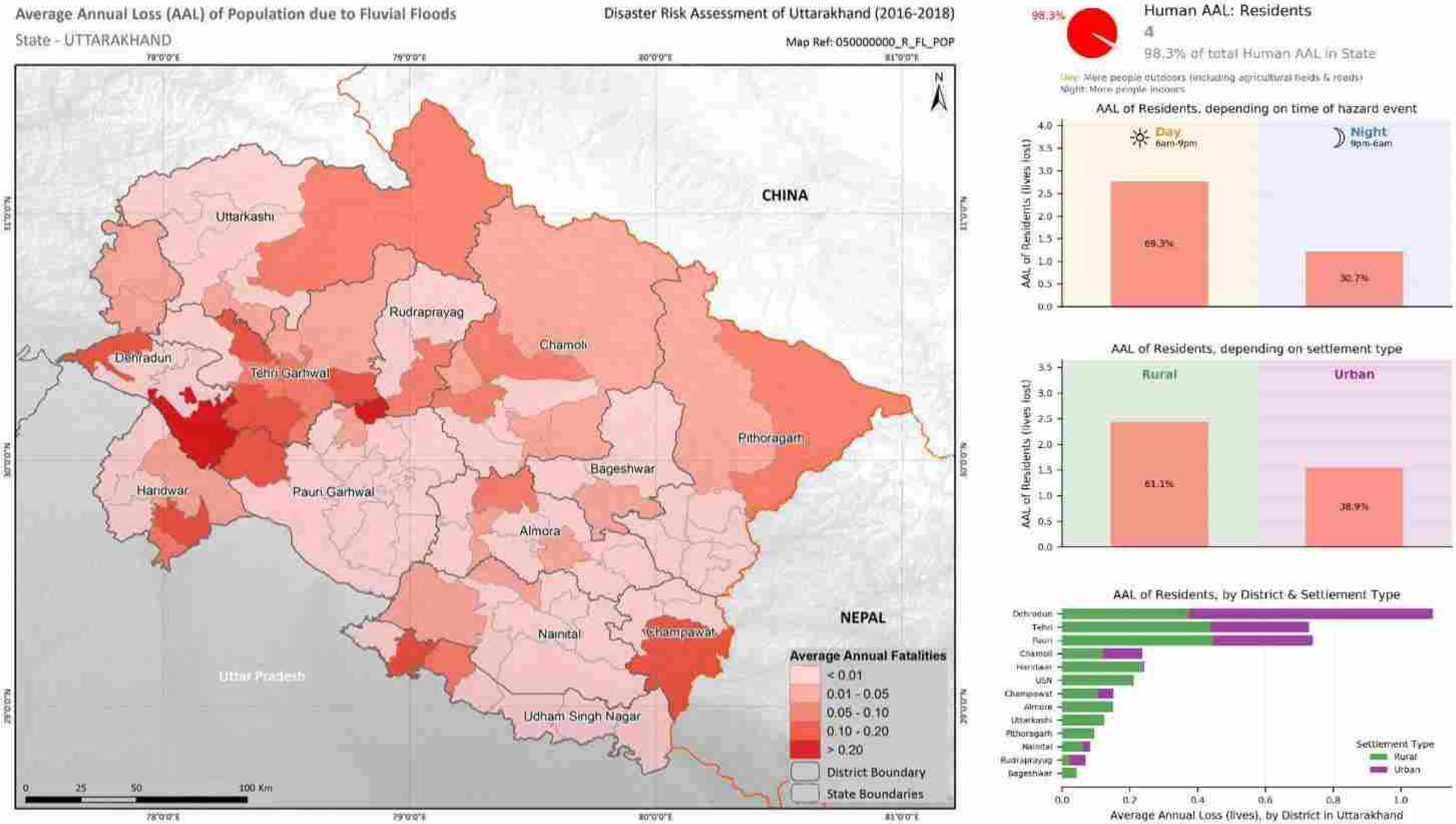

Figure 3.107: Average Annual Loss (AAL) of human lives (residents) due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.108 presents the PML curve for human lives (residents) in the state, for two sets of assumptions: standard protection (people protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

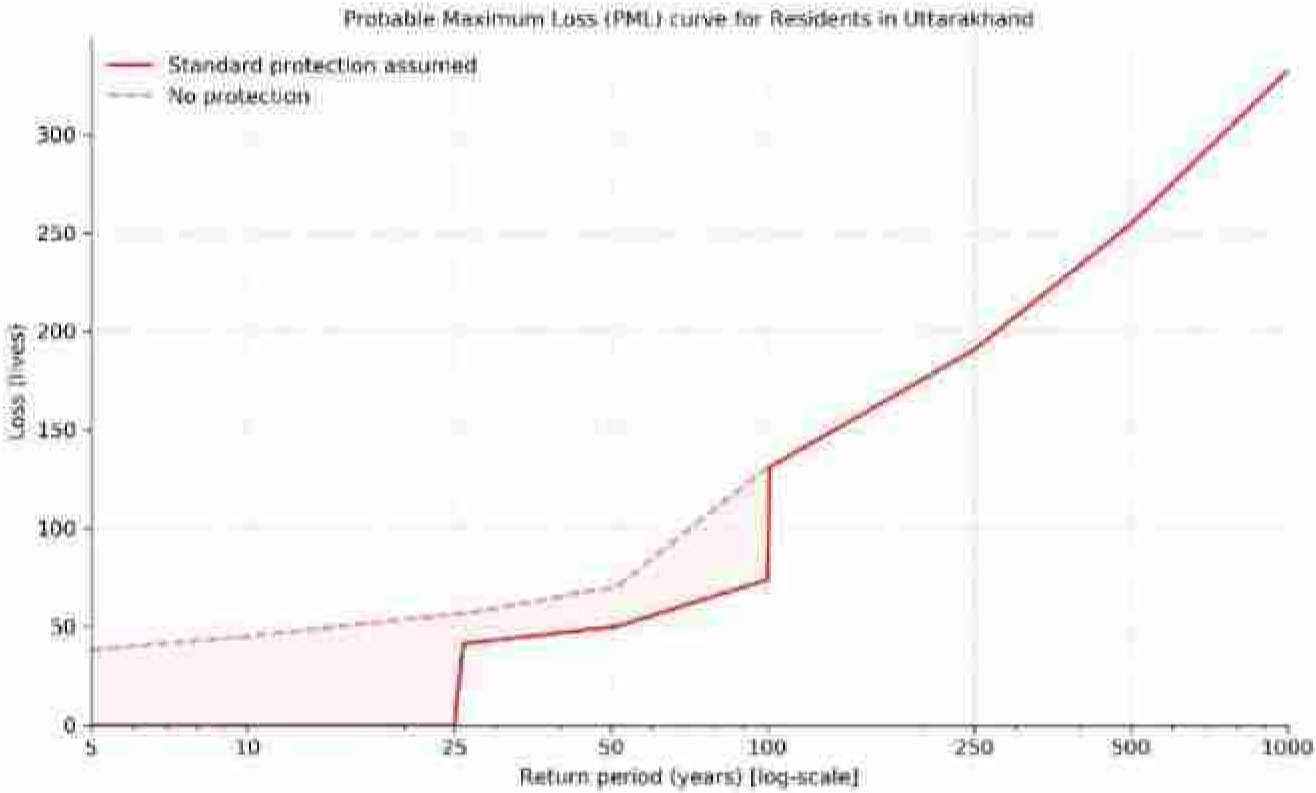

Figure 3.108: Probable Maximum Loss (PML) curve for human lives (residents) in Uttarakhand due to fluvial floods

Figure 3.109 shows the Average Annual Loss (AAL) of human lives (tourists) due to fluvial flood hazards.

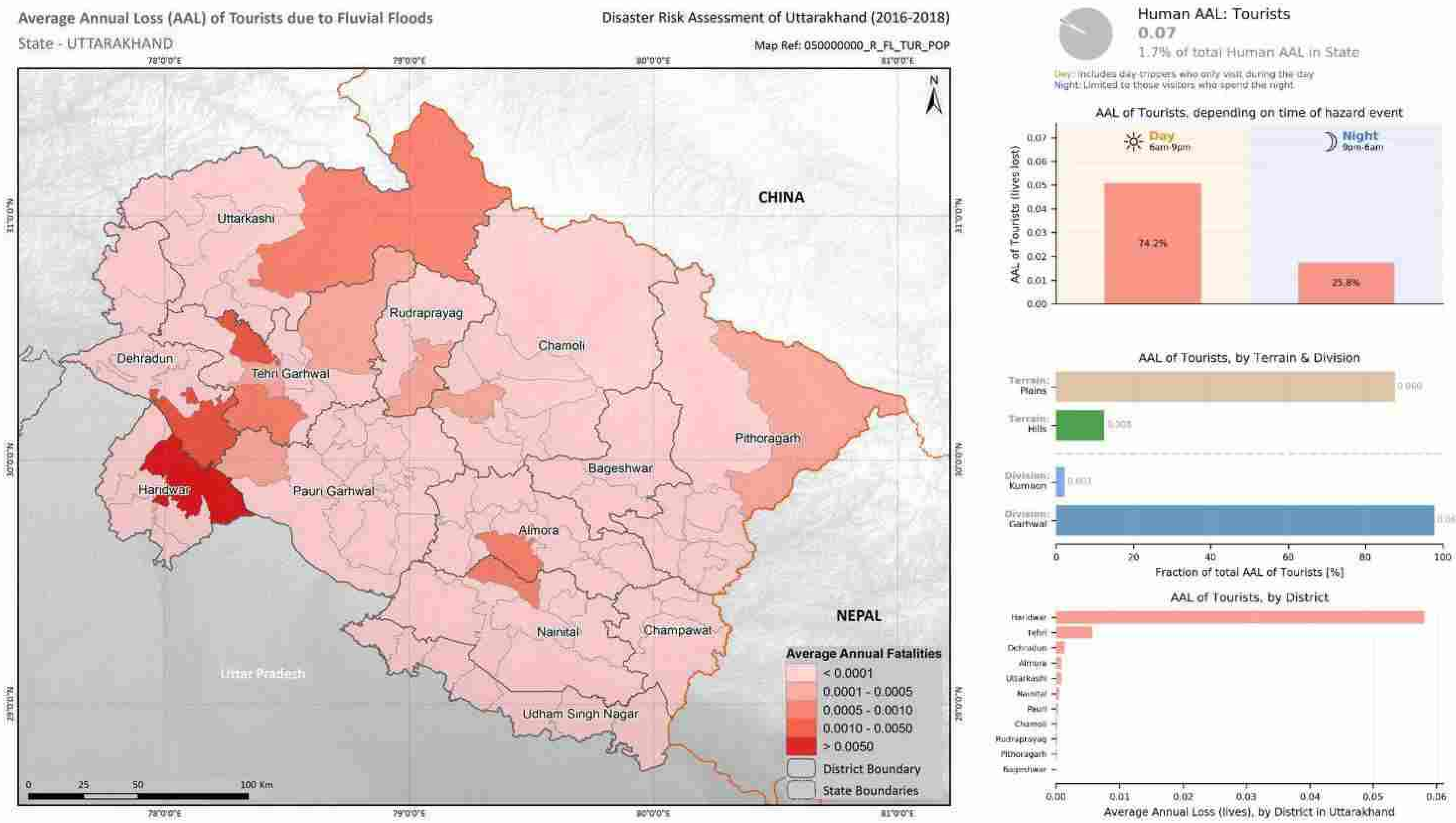

Figure 3.109: Average Annual Loss (AAL) of human lives (tourists) due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.110 presents the PML curve for human lives (tourists) in the state, for two sets of assumptions: standard protection (people protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

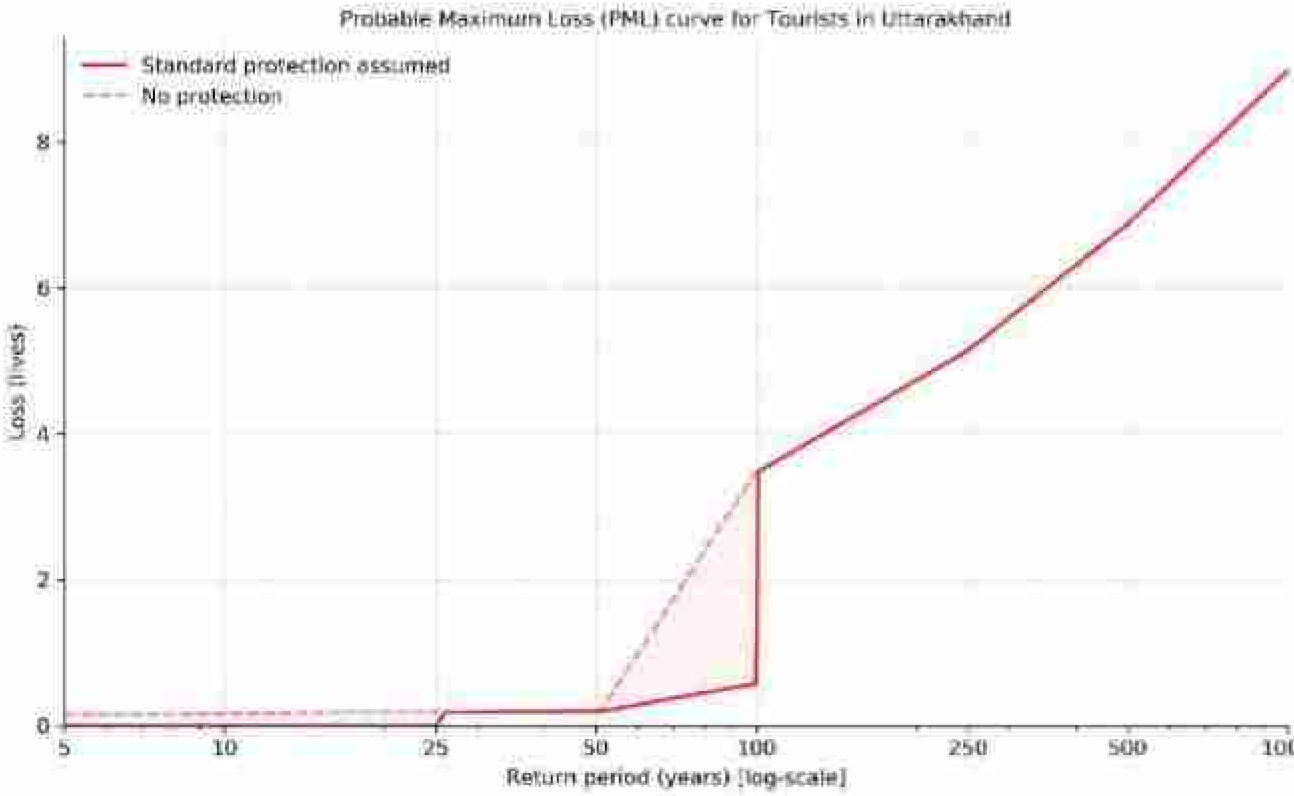

Figure 3.110: Probable Maximum Loss (PML) curve for human lives (tourists) in Uttarakhand due to fluvial floods

3.4.11 Residential building losses due to floods (fluvial)

Figure 3.111 shows the Average Annual Loss (AAL) of residential buildings due to fluvial flood hazards.

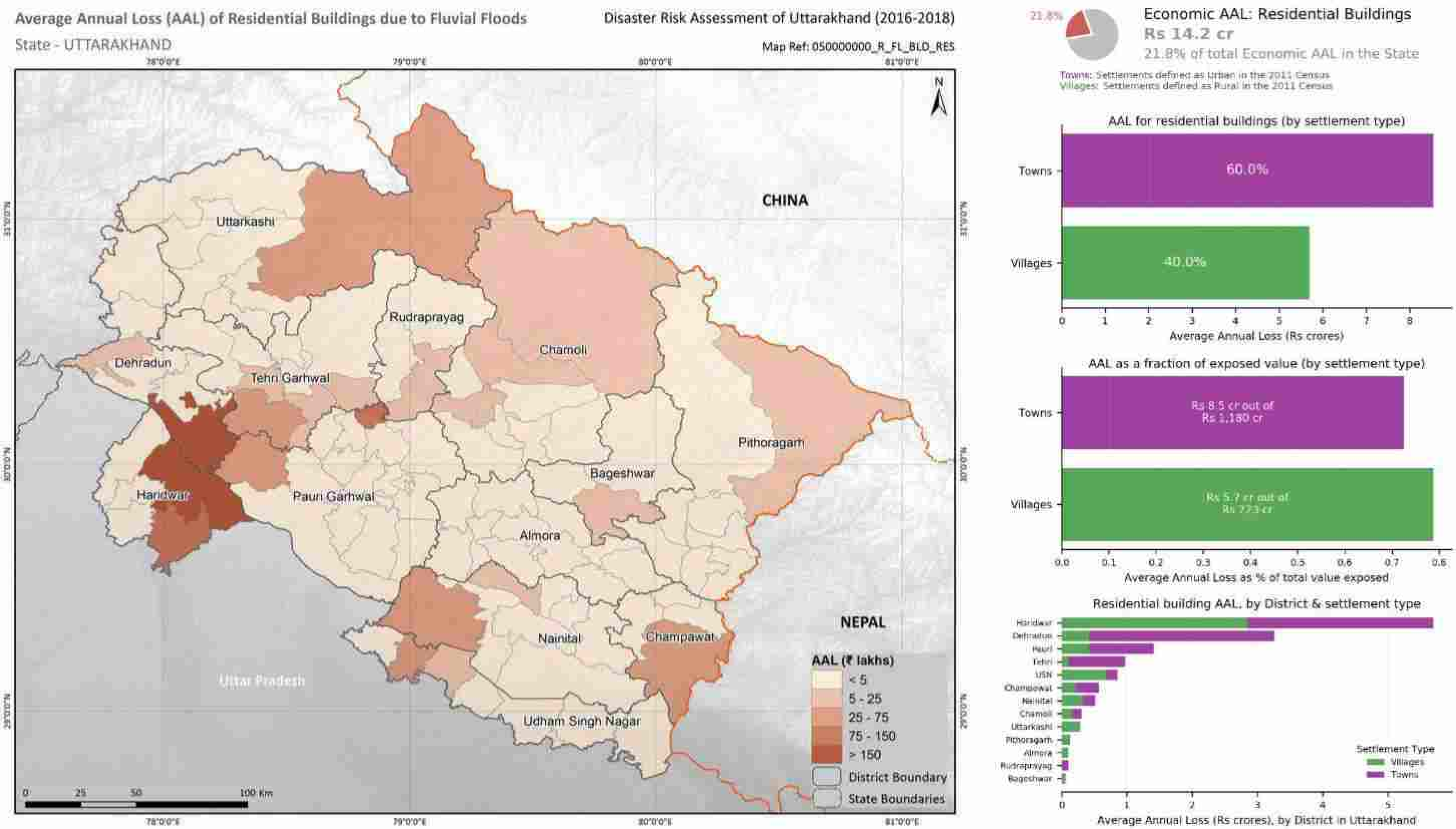

Figure 3.111: Average Annual Loss (AAL) of residential buildings due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.112 presents the PML curve for residential buildings in the state, for two sets of assumptions: standard protection (built exposure protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

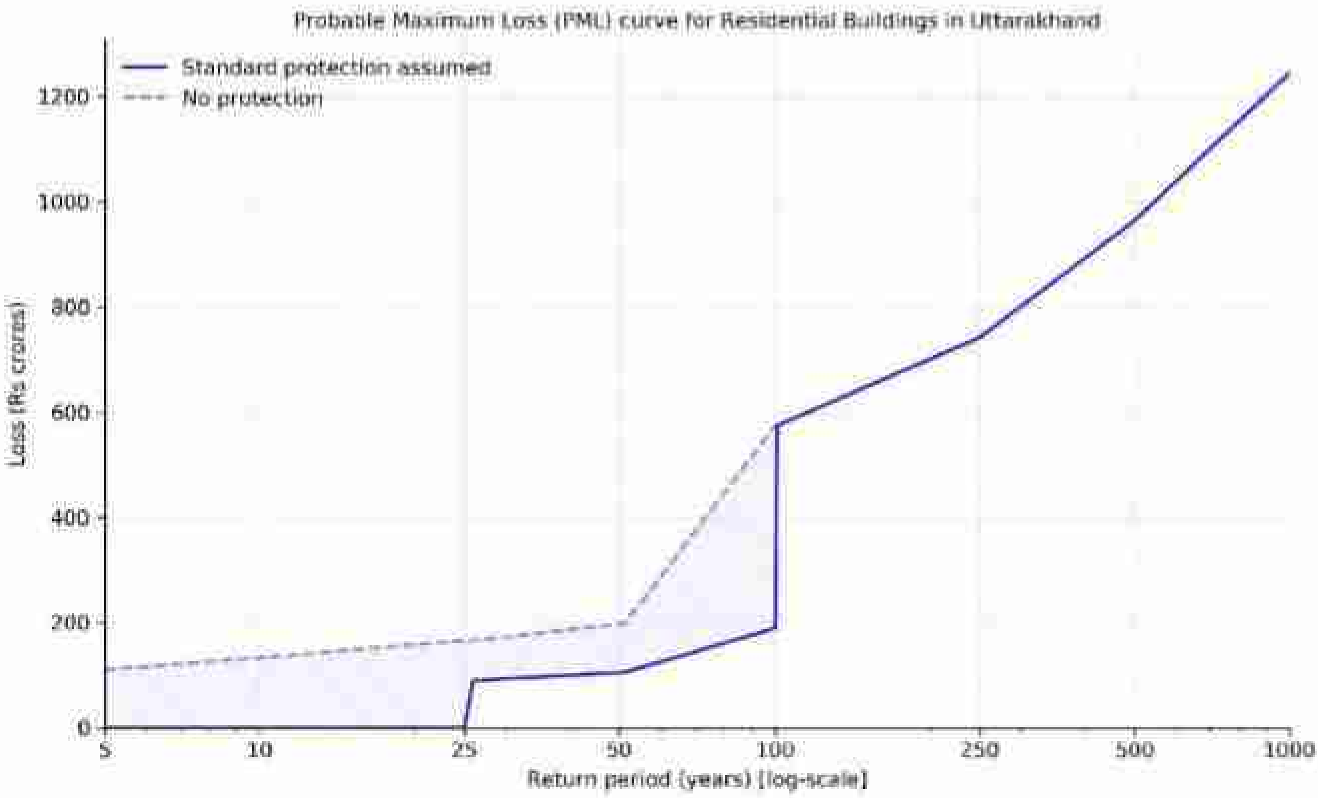

Figure 3.112: Probable Maximum Loss (PML) curve for residential buildings in Uttarakhand due to fluvial floods

3.4.12 Critical building losses due to floods (fluvial)

Figure 3.113 shows the Average Annual Loss (AAL) of critical buildings due to fluvial flood hazards.

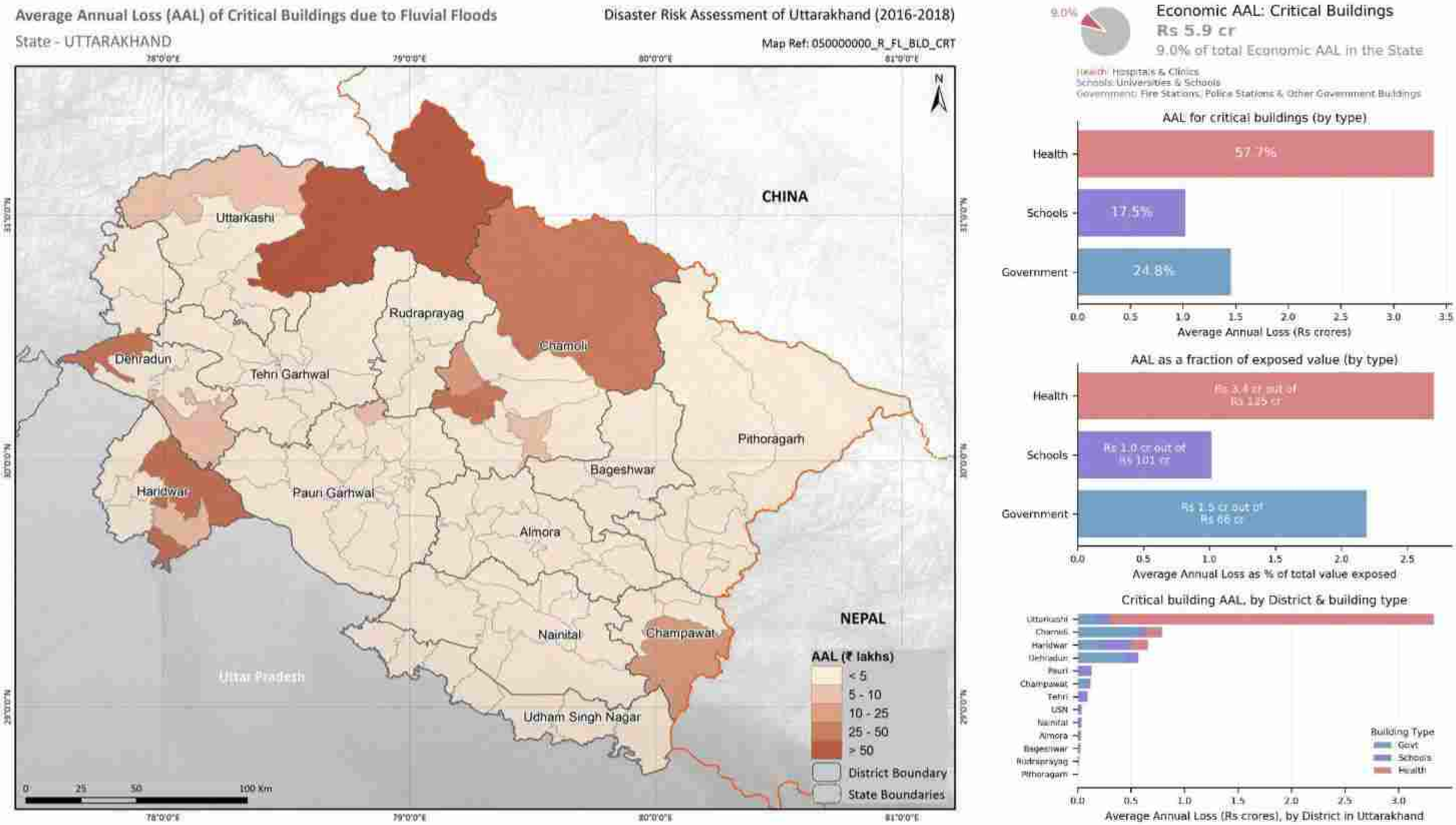

Figure 3.113: Average Annual Loss (AAL) of critical buildings due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.114 below presents the PML curve for critical buildings in the state, for two sets of assumptions: standard protection (built exposure protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

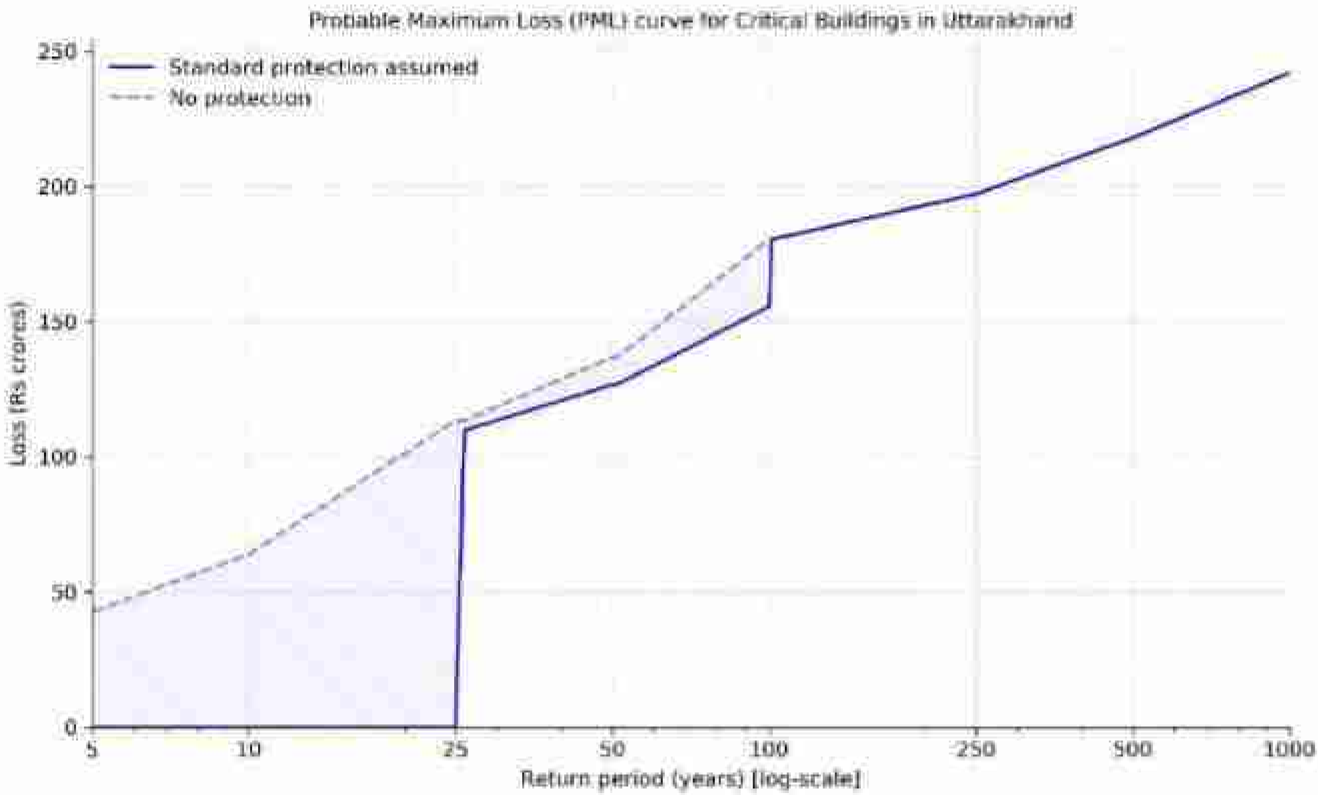

Figure 3.114: Probable Maximum Loss (PML) curve for critical buildings in Uttarakhand due to fluvial floods

3.4.13 Transportation infrastructure losses due to floods (fluvial)

Figure 3.115 shows the Average Annual Loss (AAL) of transportation infrastructure due to fluvial flood hazards.

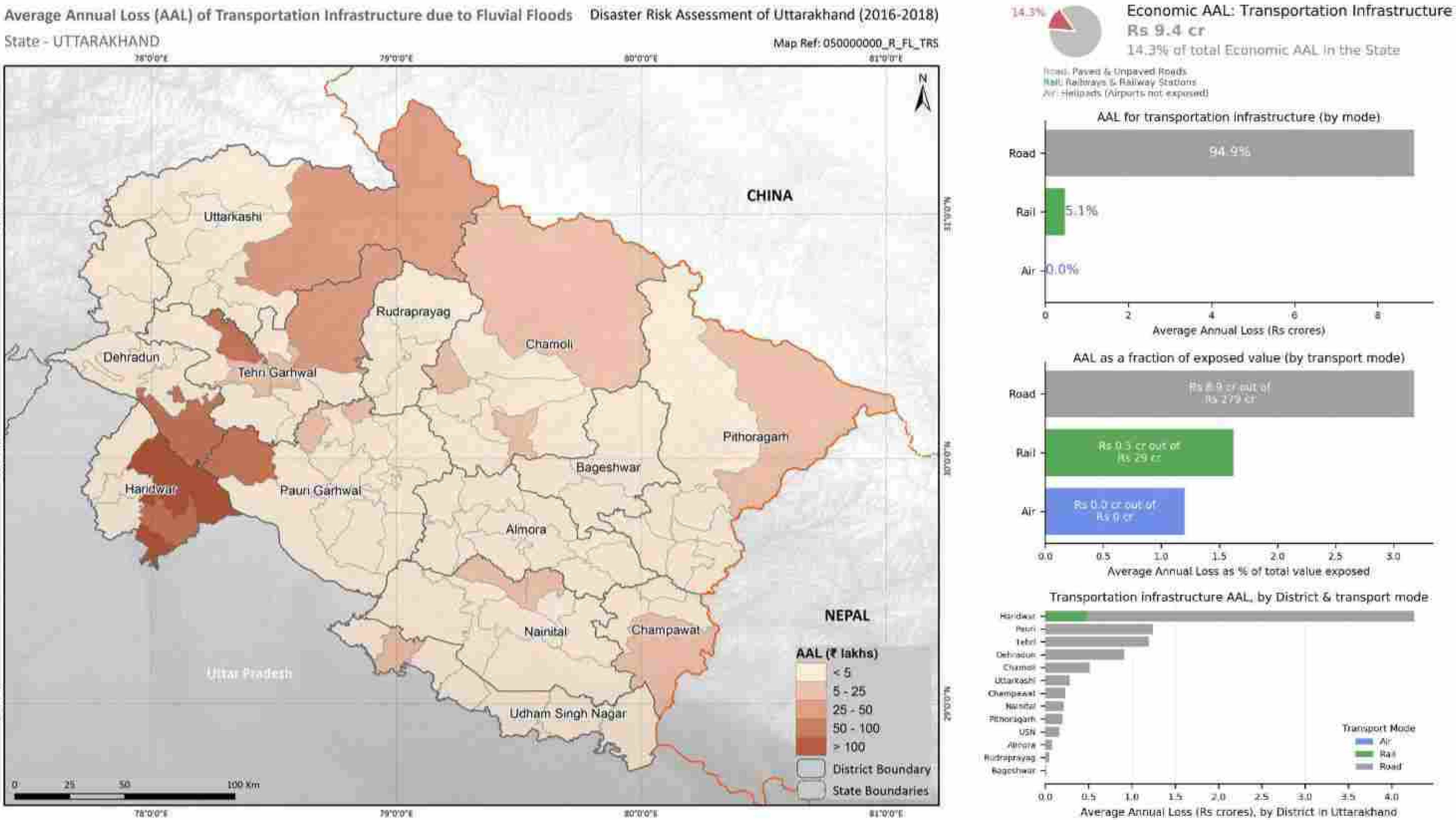

Figure 3.115: Average Annual Loss (AAL) of transportation infrastructure due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.116 presents the PML curve for transportation infrastructure in the state. Note that only one version of the curve is presented for transportation infrastructure, based on the assumption of no protection (given the wide spatial distribution of the exposure elements making up this portfolio).

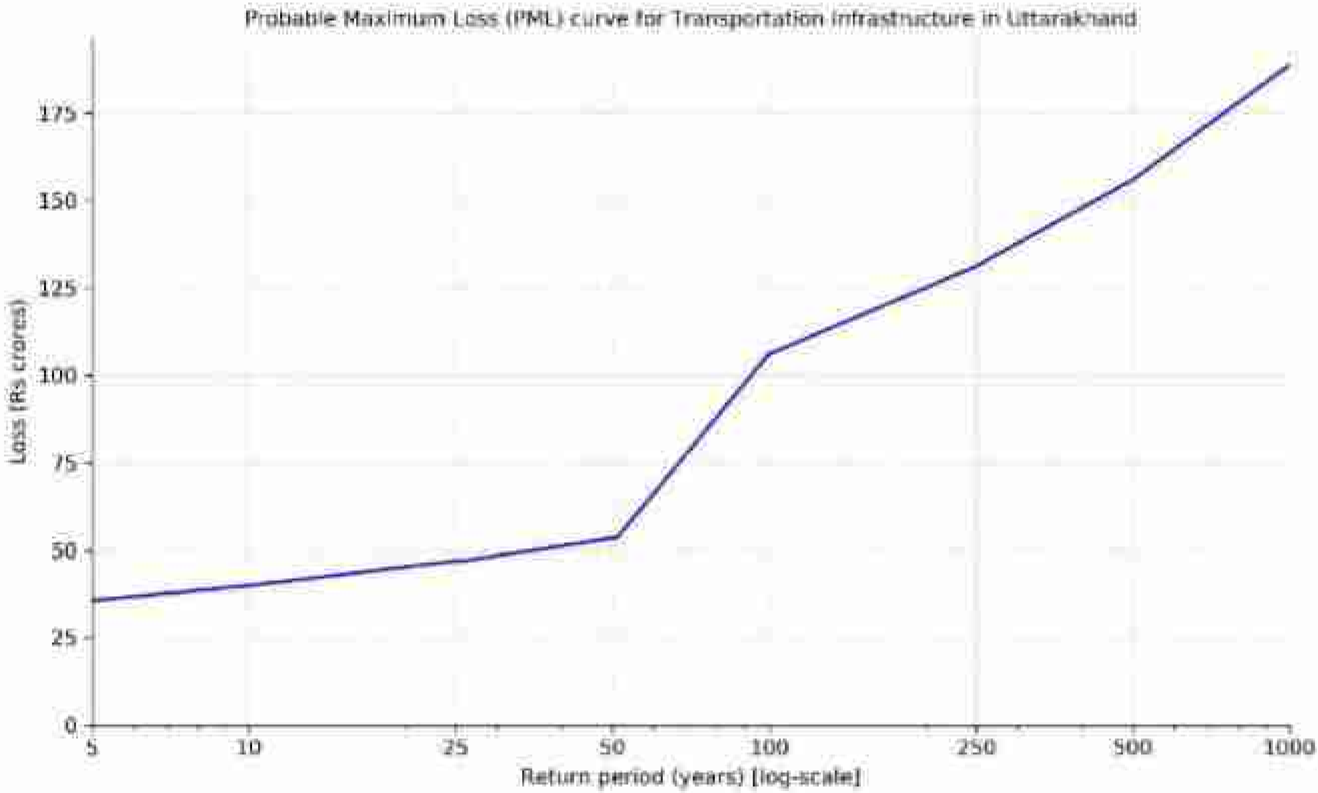

Figure 3.116. Probable Maximum Loss (PML) curve for transportation infrastructure in Uttarakhand due to fluvial floods

3.4.14 Power infrastructure losses due to floods (fluvial)

Figure 3.117 shows the Average Annual Loss (AAL) of power infrastructure due to fluvial flood hazards.

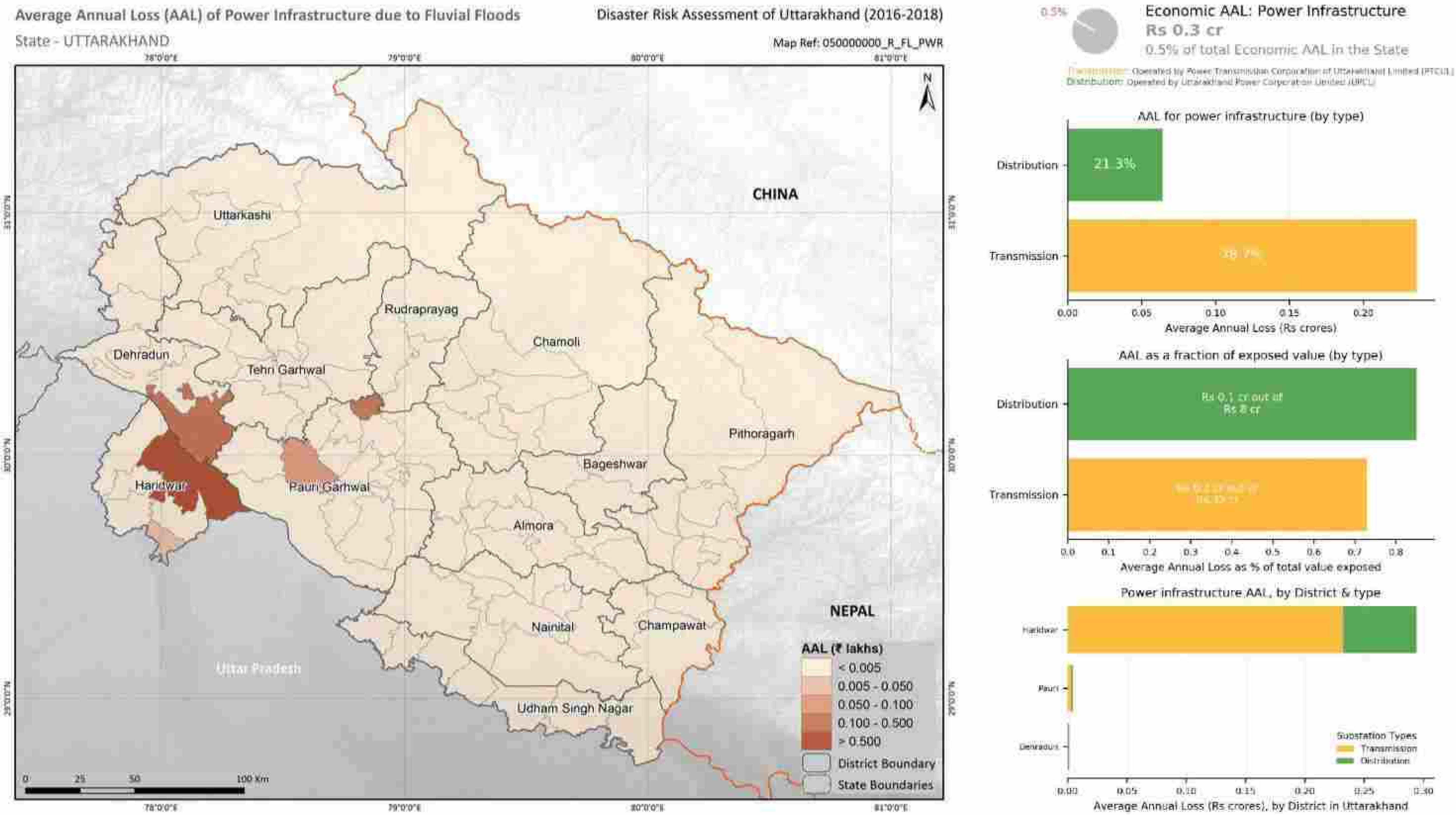

Figure 3.117: Average Annual Loss (AAL) of power infrastructure due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.118 presents the PML curve for power infrastructure in the state, for two sets of assumptions: standard protection (built exposure protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

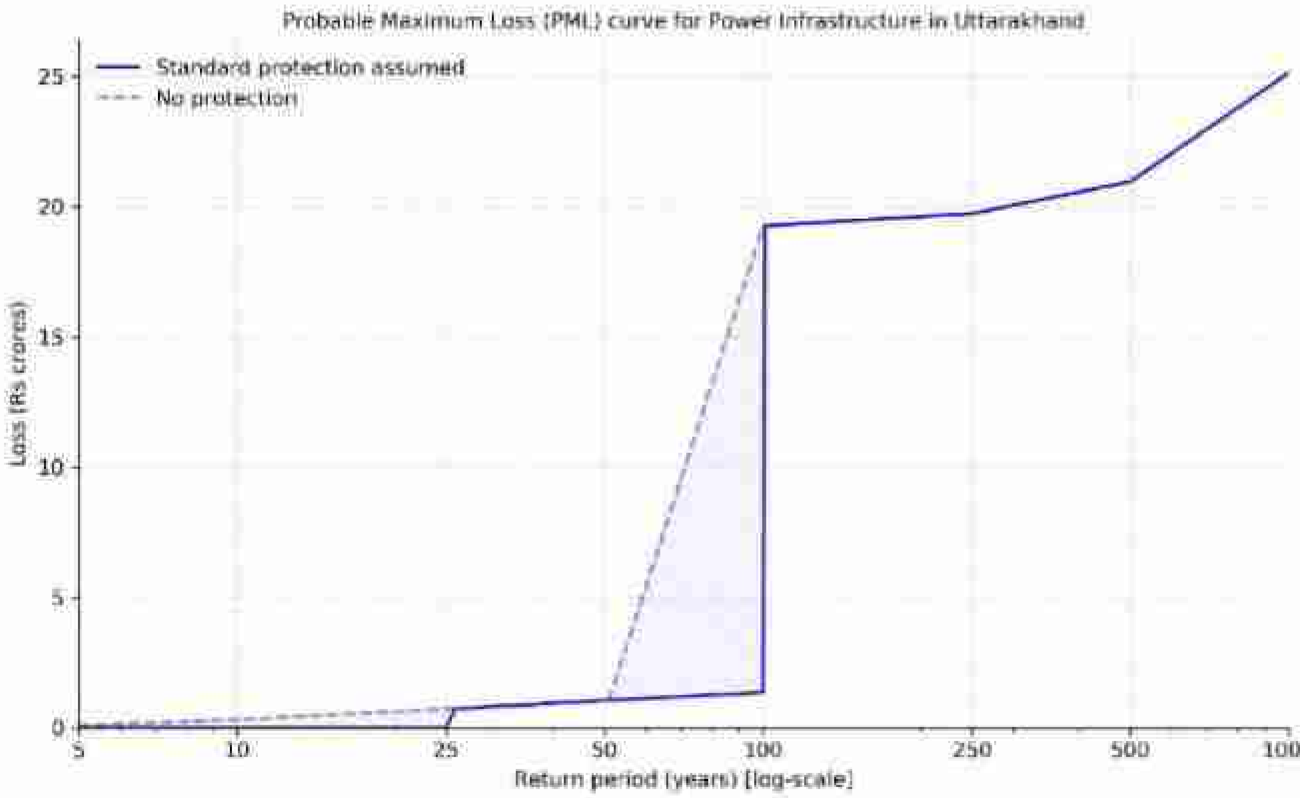

Figure 3.118: Probable Maximum Loss (PML) curve for power infrastructure in Uttarakhand due to fluvial floods

3.4.15 Economic sectors

Figure 3.119 shows the Average Annual Loss (AAL) of agriculture due to fluvial flood hazards.

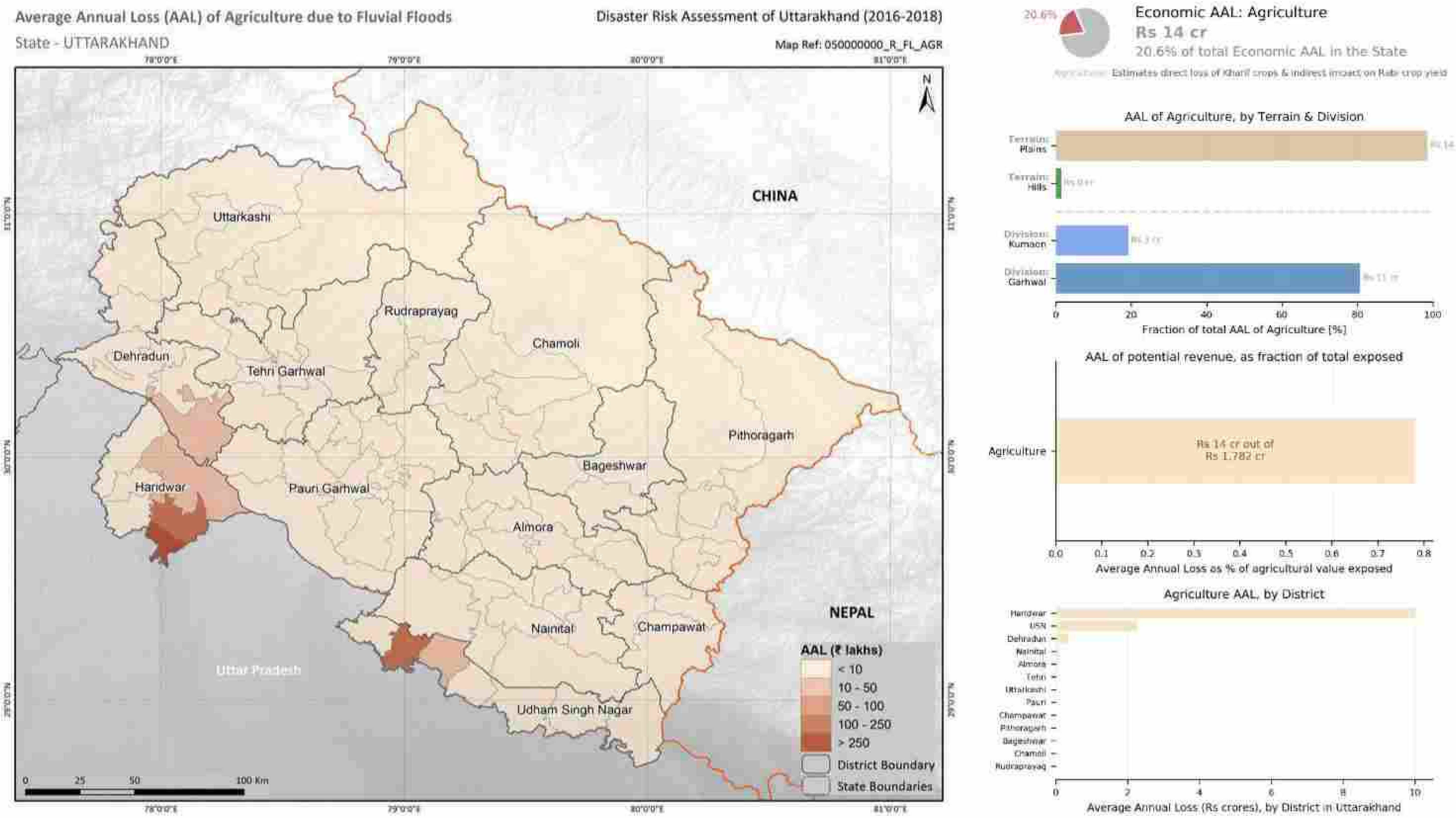

Figure 3.119: Average Annual Loss (AAL) of agriculture due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.120 presents the PML curve for agriculture in the state. Note that only one version of the curve is presented for agriculture, based on the assumption of no protection (given the wide spatial distribution of the exposure elements making up this portfolio).

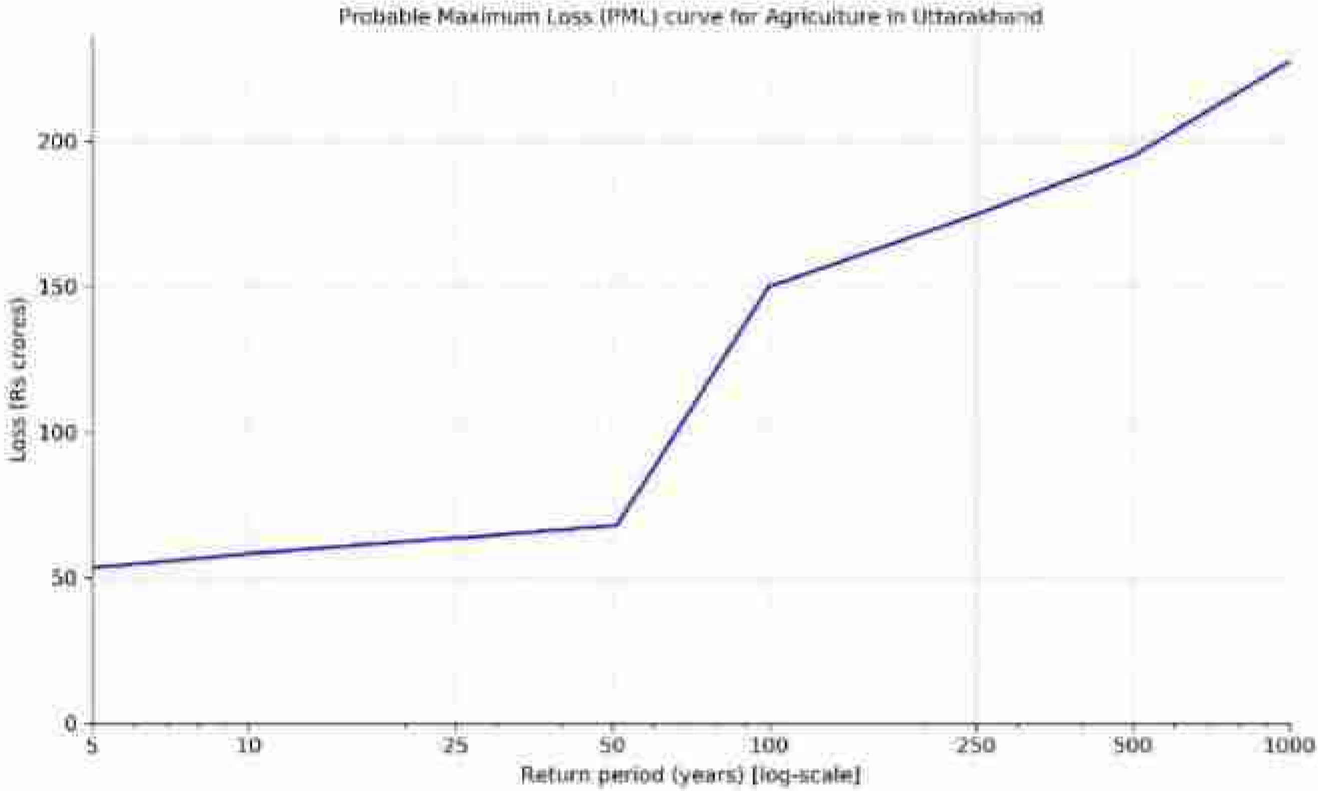

Figure 3.120: Probable Maximum Loss (PML) curve for agriculture in Uttarakhand due to fluvial floods

Figure 3.121 shows the Average Annual Loss (AAL) of horticulture due to fluvial flood hazards.

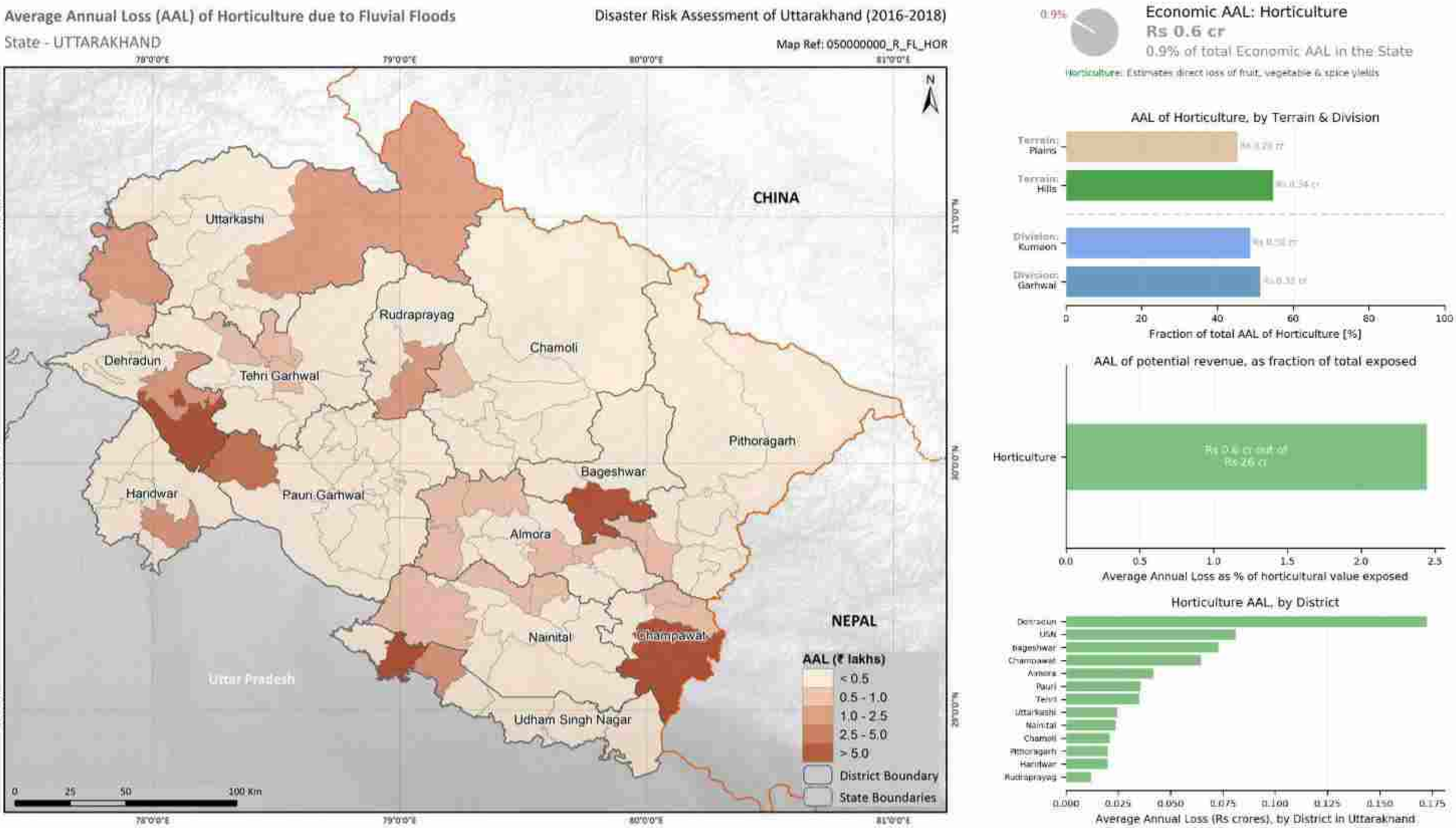

Figure 3.121: Average Annual Loss (AAL) of horticulture due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.122 presents the PML curve for horticulture in the state. Note that only one version of the curve is presented for horticulture, based on the assumption of no protection (given the wide spatial distribution of the exposure elements making up this portfolio).

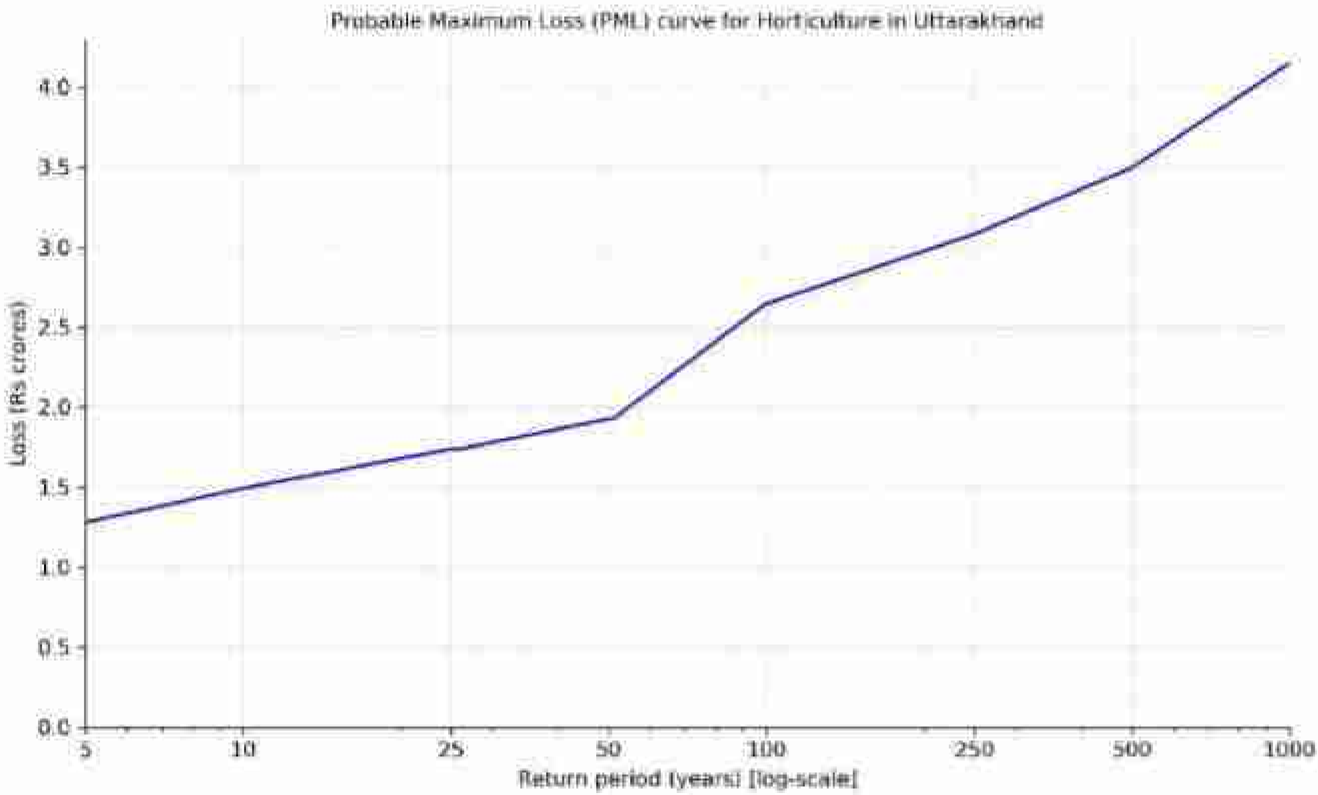

Figure 3.122: Probable Maximum Loss (PML) curve for horticulture in Uttarakhand due to fluvial floods

Figure 3.123 shows the Average Annual Loss (AAL) of industry, commerce and mining due to fluvial flood hazards.

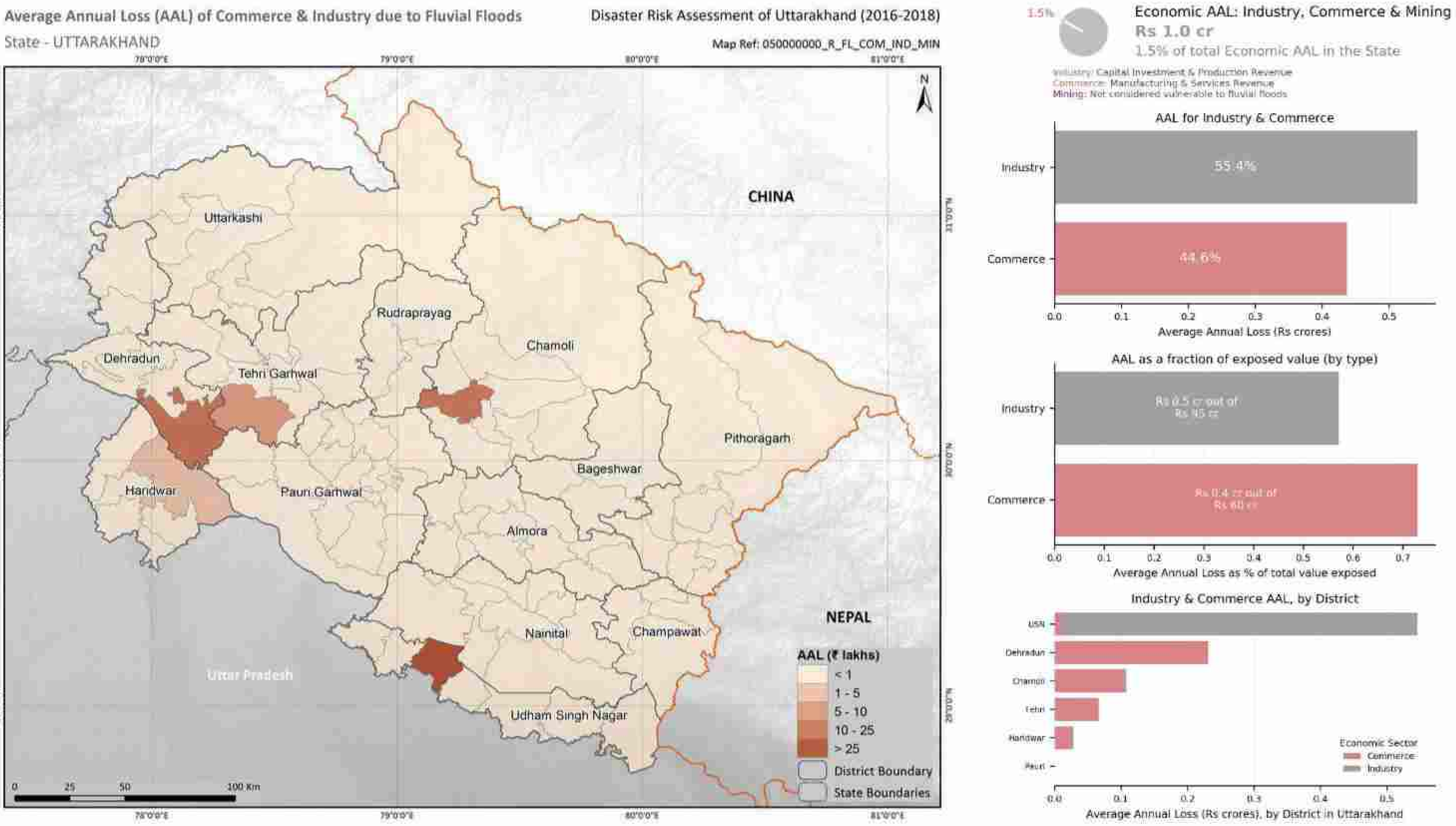

Figure 3.123: Average Annual Loss (AAL) of industry, commerce and mining due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.124 presents the PML curve for commerce and industry in the state, for two sets of assumptions: standard protection (built exposure protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

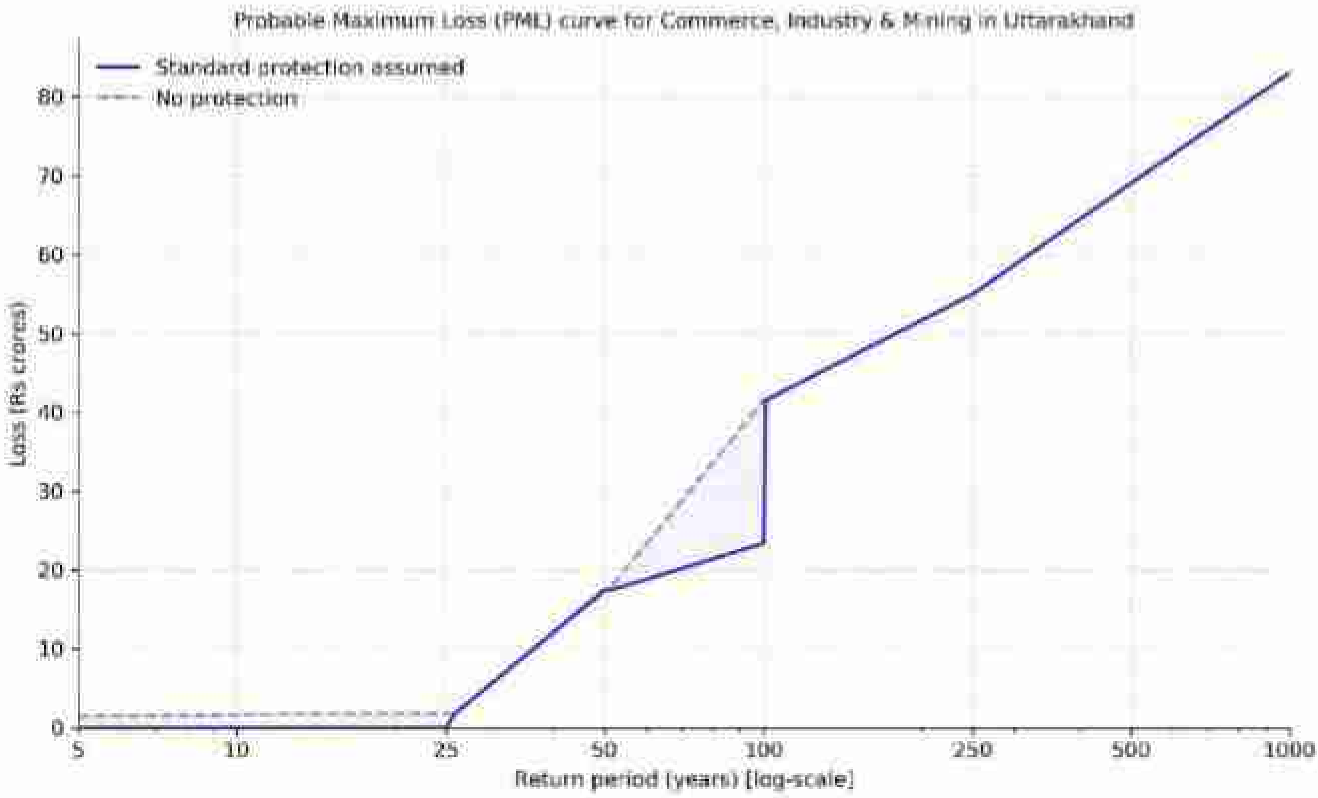

Figure 3.124: Probable Maximum Loss (PML) curve for commerce and industry in Uttarakhand due to fluvial floods

Figure 3.125 shows the Average Annual Loss (AAL) of potential future tourism revenue due to fluvial flood hazards.

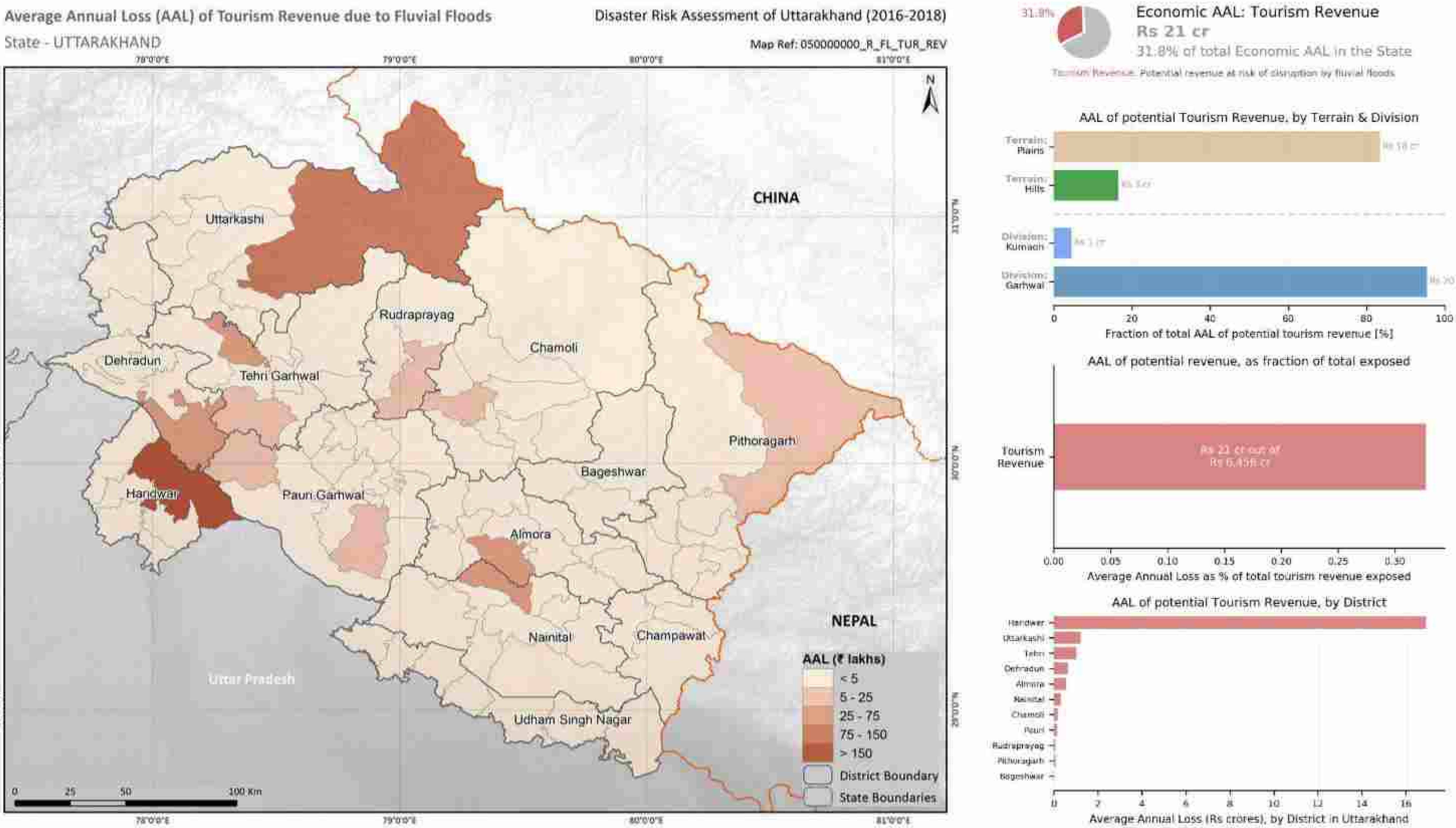

Figure 3.125: Average Annual Loss (AAL) of potential (future) tourism revenue due to fluvial floods

Probable Maximum Loss (PML) curves show the maximum losses that could reasonably be expected for exposed assets, for a range of different return periods. Figure 3.126 presents the PML curve for tourism revenue in the state, for two sets of assumptions: standard protection (built exposure protected up to the 25 year event in villages and the 100 year event in towns) and no protection at all. The reality is likely to be somewhere in between.

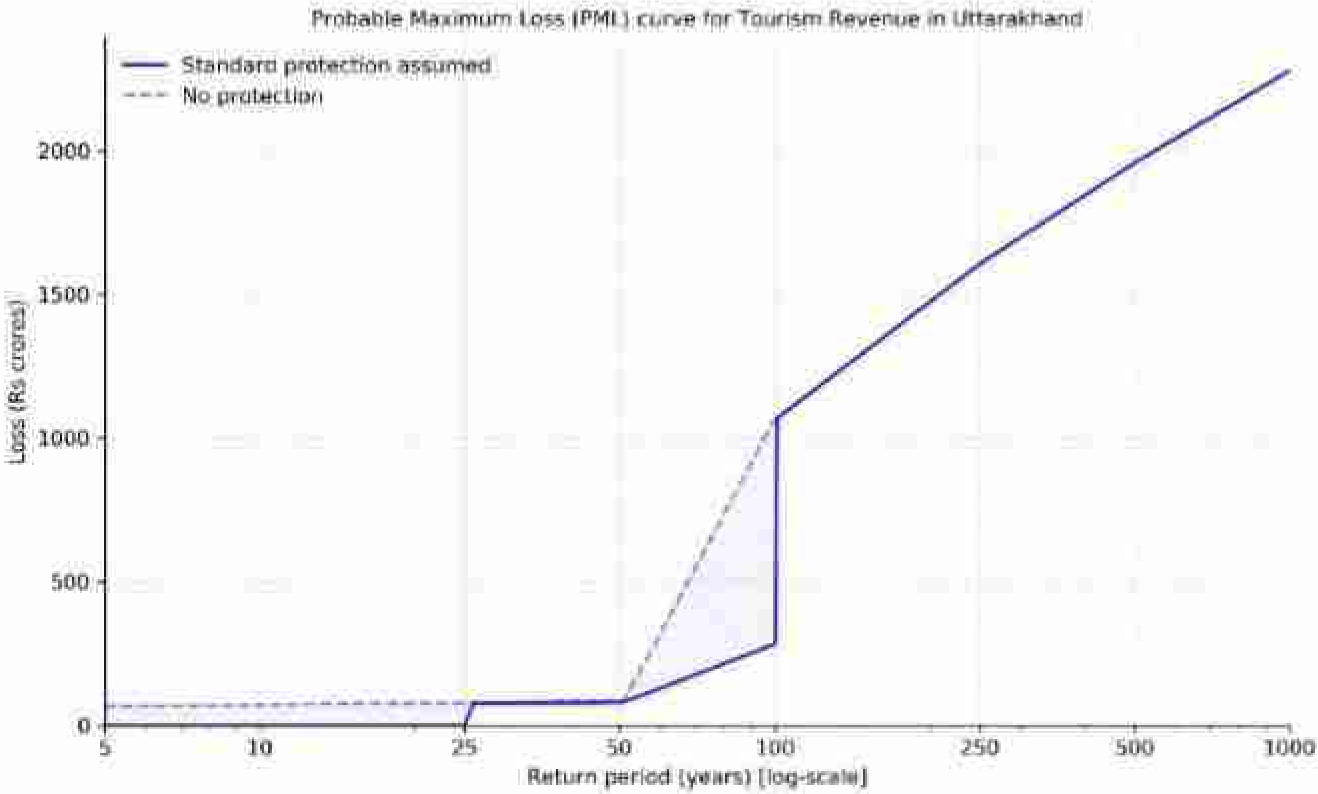

Figure 3.126: Probable Maximum Loss (PML) curve for tourism revenue in Uttarakhand due to fluvial floods

3.5 Landslides

Hazard Profile

Landslide susceptibility modelling has been executed using a series of district-level Maxent models (with the exception of Udham Singh Nagar district, where no historical landslides have yet been recorded and which could therefore not be modelled). Further details on the modelling methodology are provided in Volume 1, Chapter 2.

In each of the district-level landslide susceptibility sections, a brief summary of that district's Maxent model is presented, giving a useful insight into which of the many input datasets proved to make the largest contributions to the model in that particular district. All of these are summarised in Figure 3.127, showing clearly the significant impact that road cuttings have, as well as topographical properties such as slope and aspect.

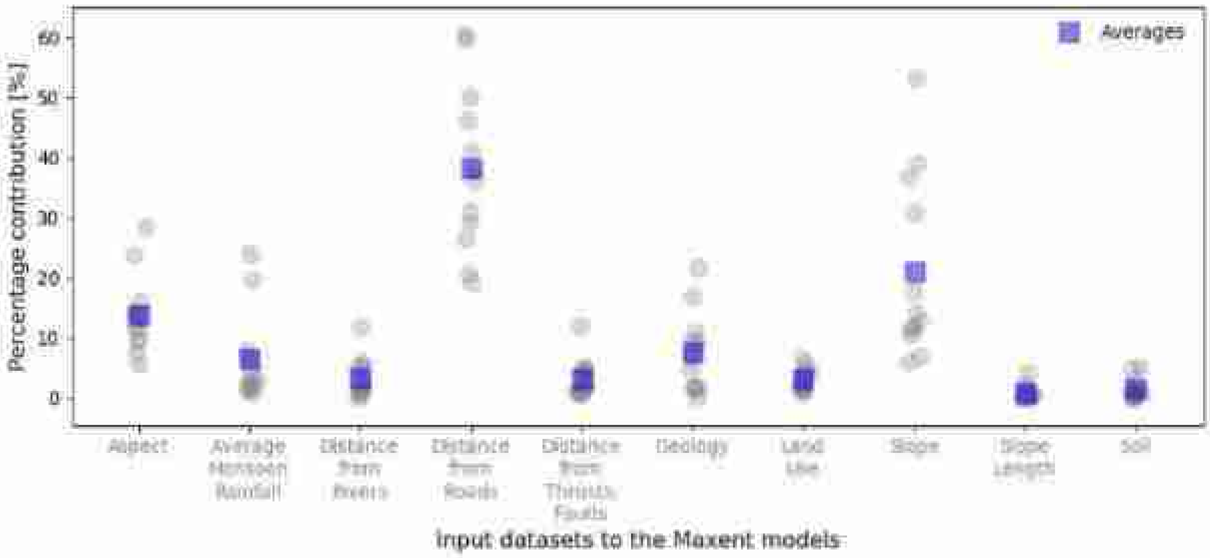

Figure 3.127: Illustration of each input dataset's contribution to the final solution, for the 12 district models run

For each district model, model performance is assessed, quantifying the benefit the model provides over a random prediction, with reference to a plot known as a Receiver Operating Characteristic (ROC) curve. This plot shows the Area Under Curve (AUC), for which a value of 0.5 is equivalent to a random prediction and a value of 1.0 would indicate a perfectly predictive model. For the district-level Maxent models run, the average train and test scores were 0.902 and 0.876, respectively, indicating a significantly superior performance over random prediction.

The results of these Maxent landslide models were reclassified into five categories, ranging from 'None' to 'Very High', in terms of landslide susceptibility. In the case of Udham Singh Nagar (for which a Maxent model could not be established) it was assumed that the district fell entirely in the 'None' category (given that no landslides have ever been reported there). Figure 3.128 shows the distribution of these classes (by area) across the entire state.

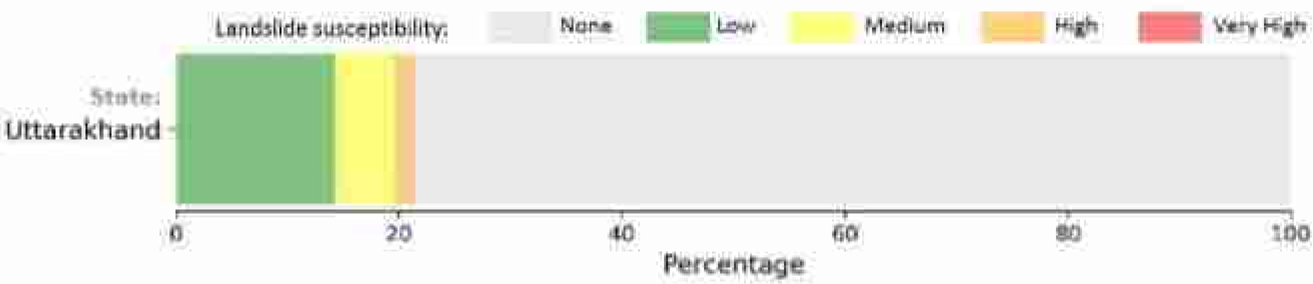

Figure 3.128: Proportions of state in the five landslide susceptibility classes

For each district and block, these distributions were also used to calculate a weighted average of the proportions covered by different classes (with higher susceptibility classes weighted more heavily). These weighted averages were used to rank all districts and blocks in the state, the results of which are shown in Figure 3.129.

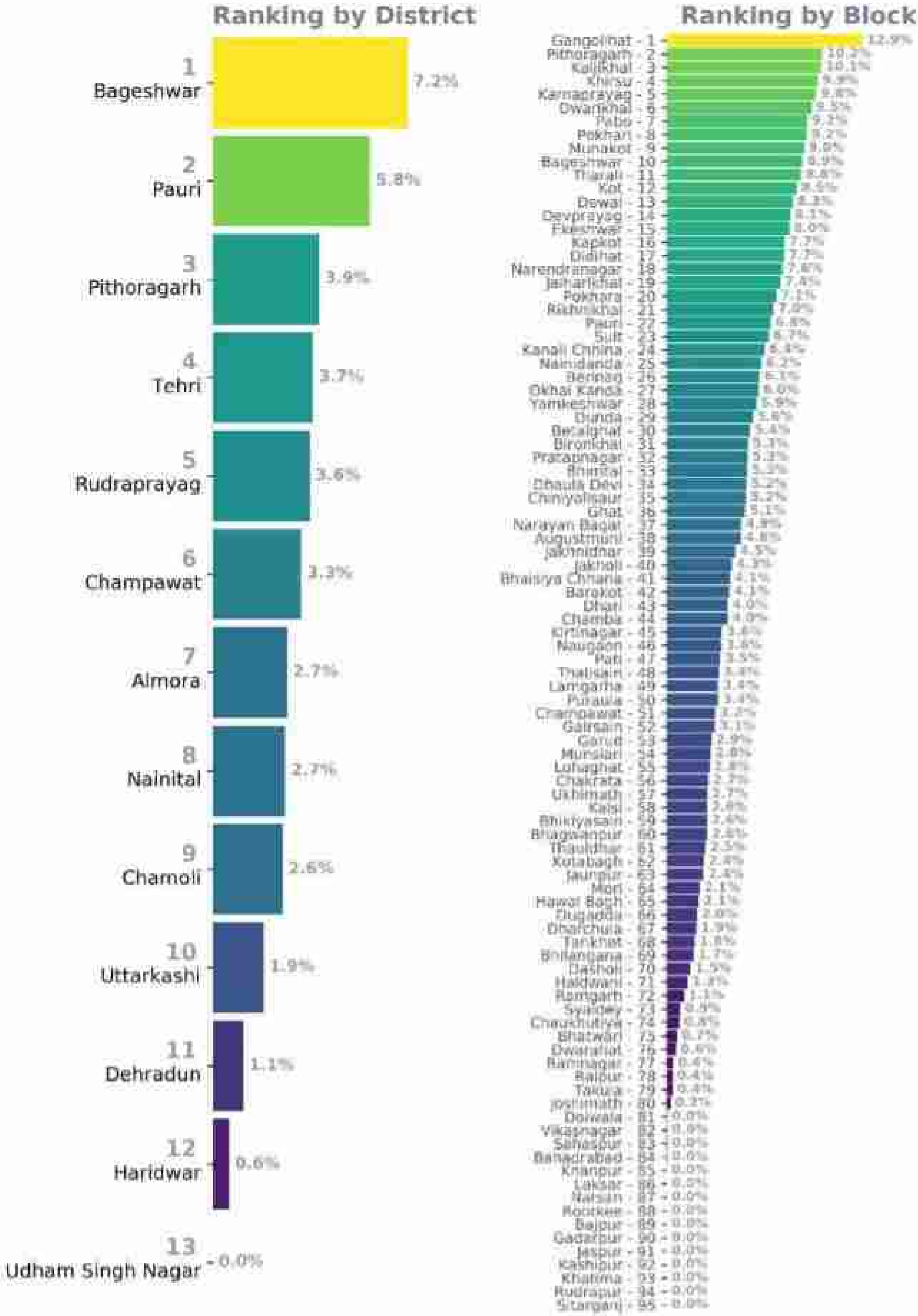

Figure 3.129: Ranking of districts (left) and blocks (right), based on a weighted average of the extent to which each is covered by different susceptibility classes (with higher susceptibility classes weighted more heavily)

3.5.1 Landslide susceptibility map

Figure 3.130 shows the modelled landslide susceptibility classes across the state of Uttarakhand, as well as its major towns.

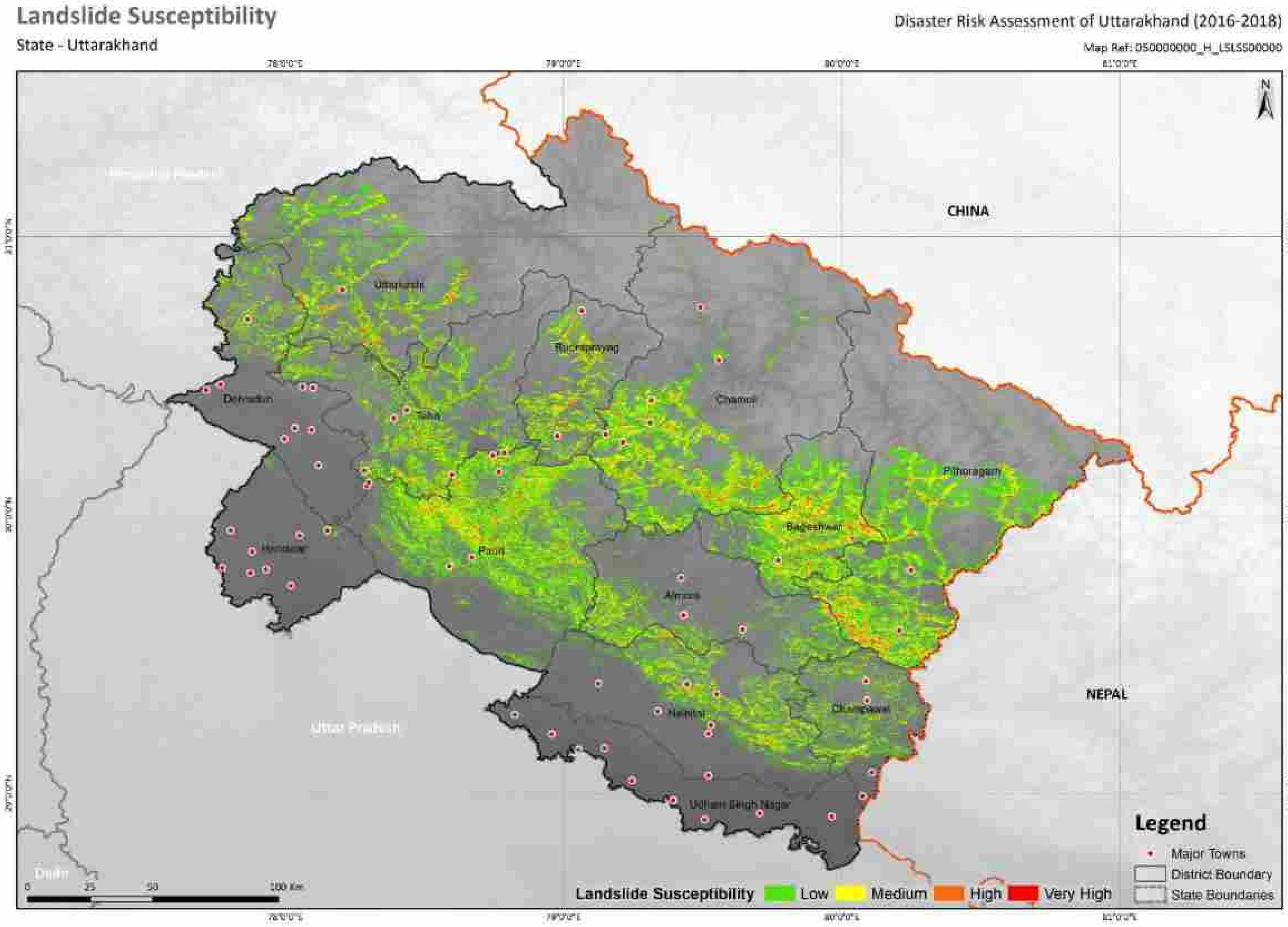

Figure 3.130: Landslide susceptibility map for the state of Uttarakhand

3.5 Landslides

/ Exposure Profile

This section presents a summary of the state's exposure to landslide susceptibility zones, with zones defined based on an equal interval classification of the range of possible susceptibility scores predicted by the Maxent models.

Rather than estimating losses, the exposure assessment only looks at the extent to which people and economic assets are exposed to different hazard intensities, providing a useful preliminary indication of impact (which isn't subject to the uncertainties associated with economic valuation and vulnerability functions).

Figure 3.131 visualises the exposure of all portfolios considered, in terms of the percentages of each population group or economic asset exposed to "limited" as opposed to "significant" landslide susceptibility zones (based on the susceptibility zone classification indicated in the figure). In the sections which follow, each portfolio will be considered separately, showing the susceptibility zones to which they are each likely to be exposed.

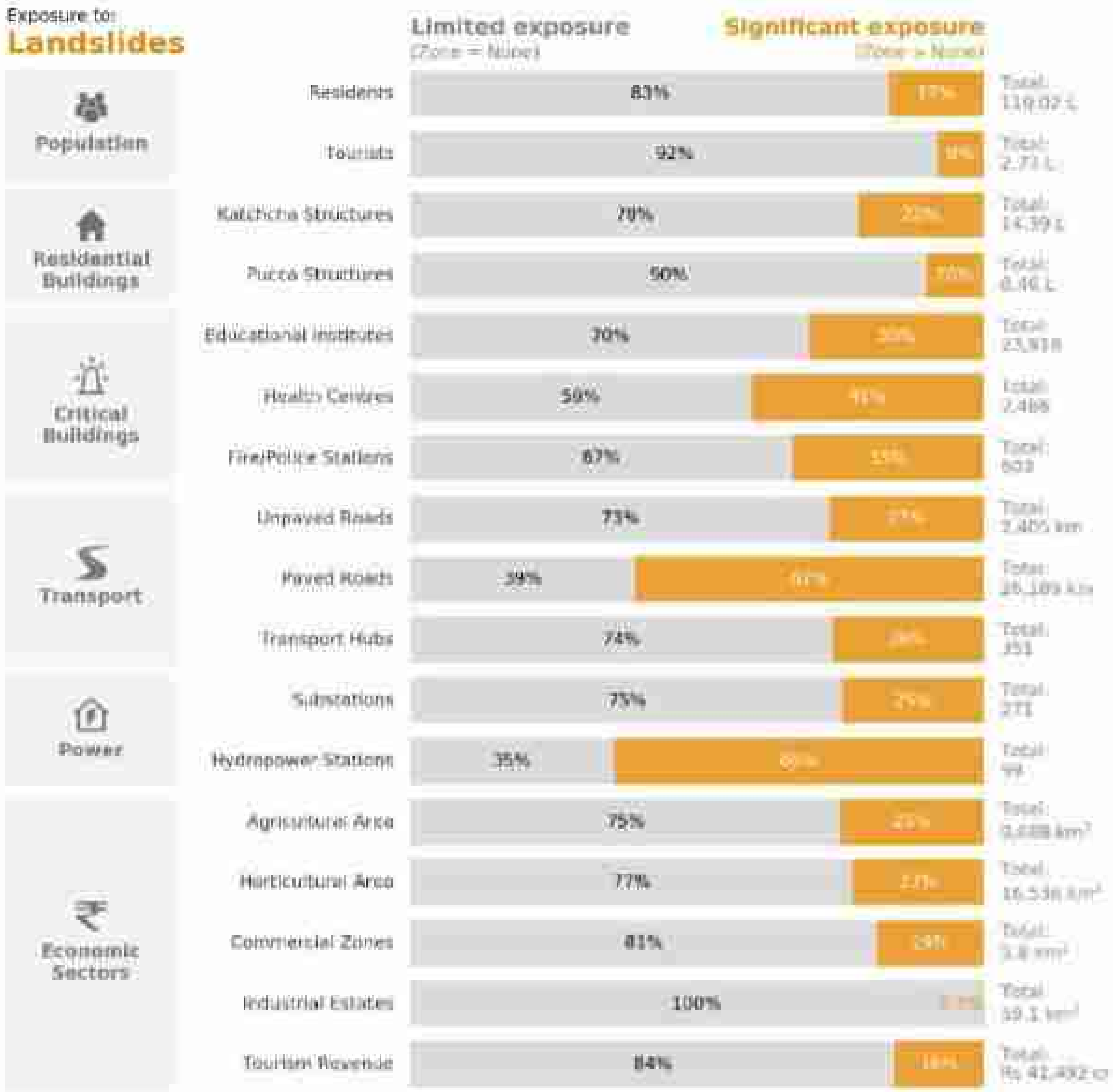

Figure 3.131: Visual summary of the State's overall exposure to landslide hazards

3.5.2 Population exposure to landslides

Figure 3.132 shows the exposure of the resident population to the various landslide susceptibility zones.

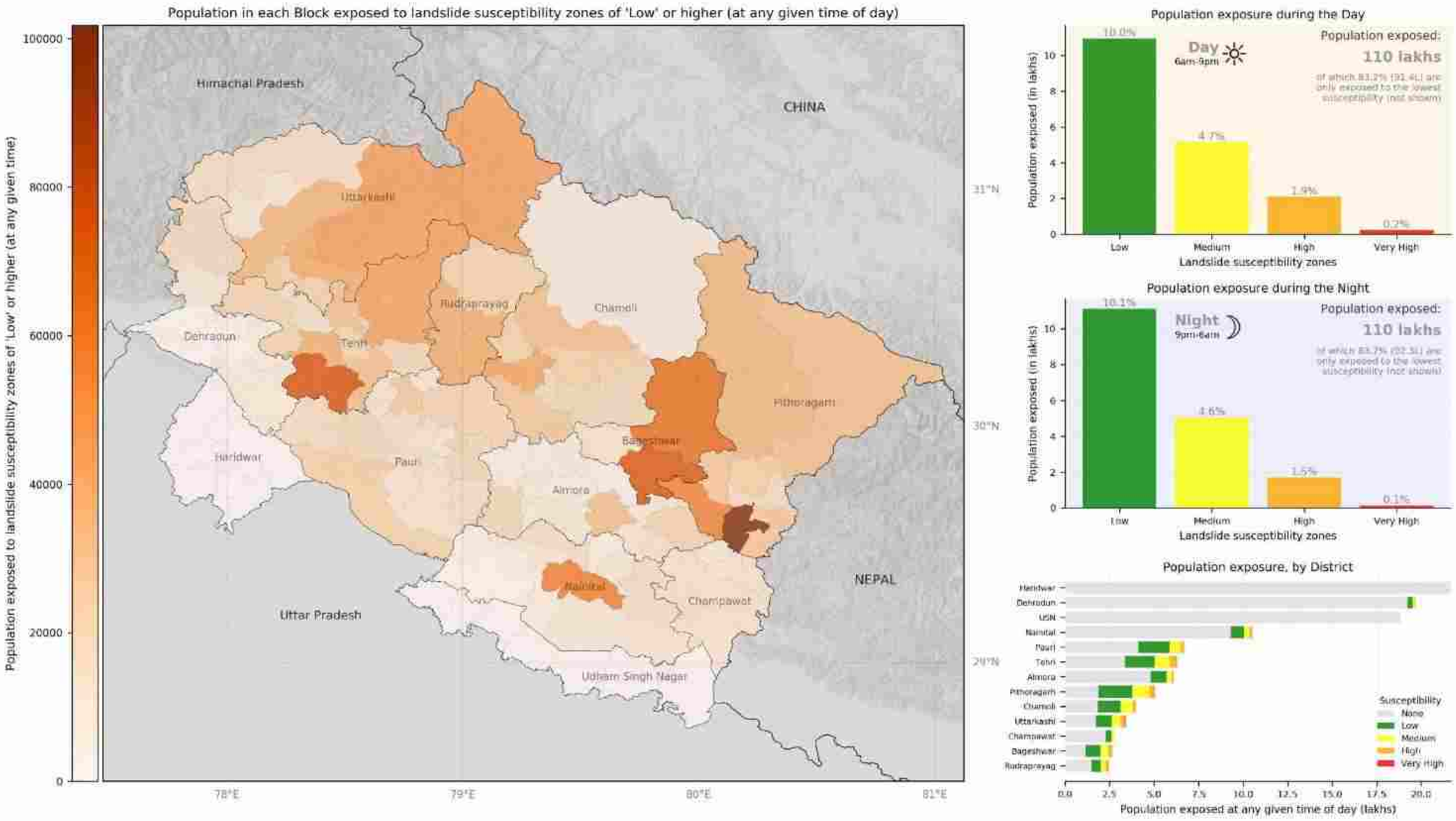

Figure 3.132: Visual summary of resident population exposed to landslide susceptibility zones

Figure 3.133 shows the exposure of tourists to the various landslide susceptibility zones. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values).

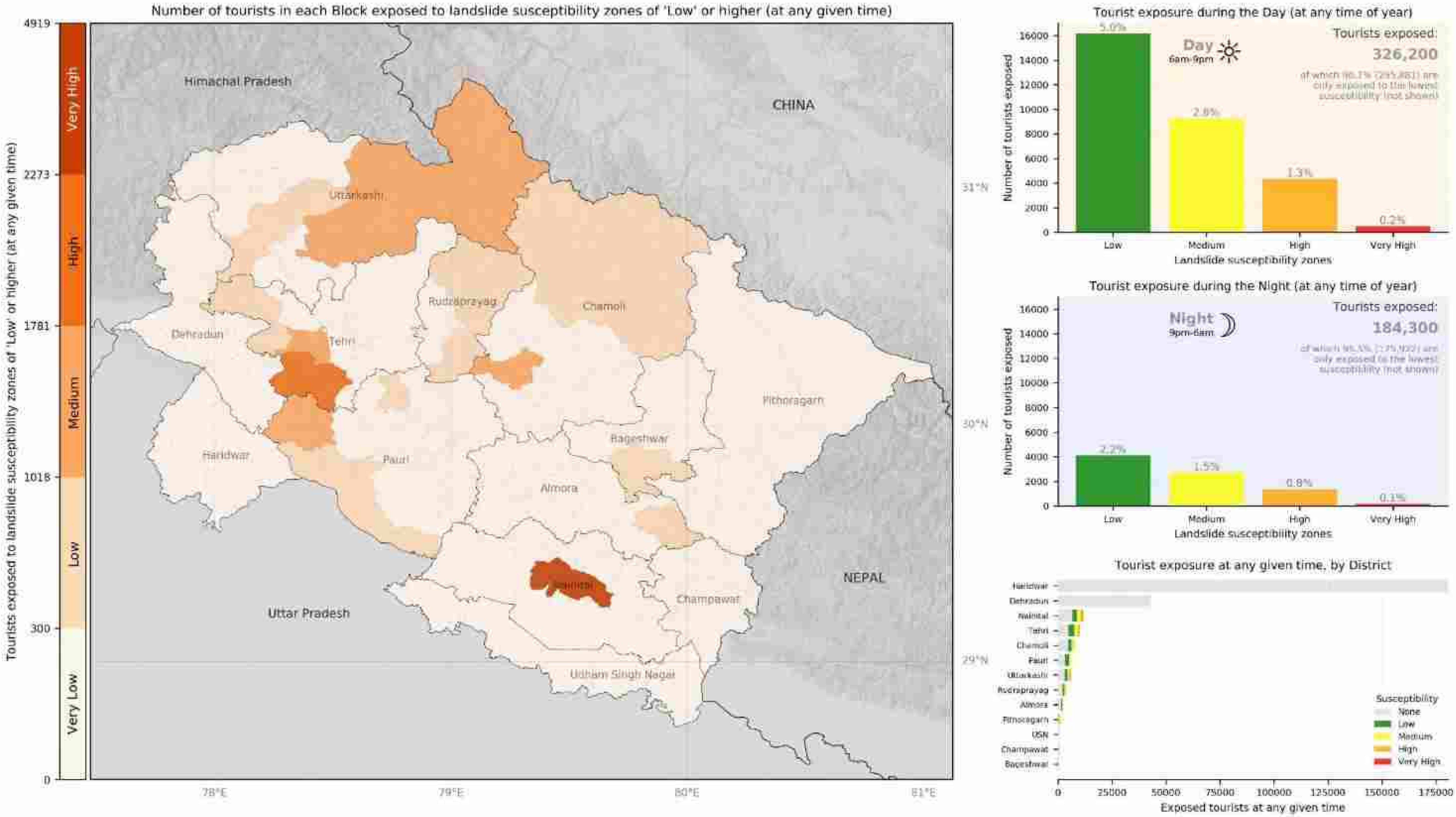

Figure 3.133: Visual summary of tourist population exposed to landslide susceptibility zones

3.5.3 Residential building exposure to landslides

Figure 3.134 shows the exposure of residential buildings to the various landslide susceptibility zones.

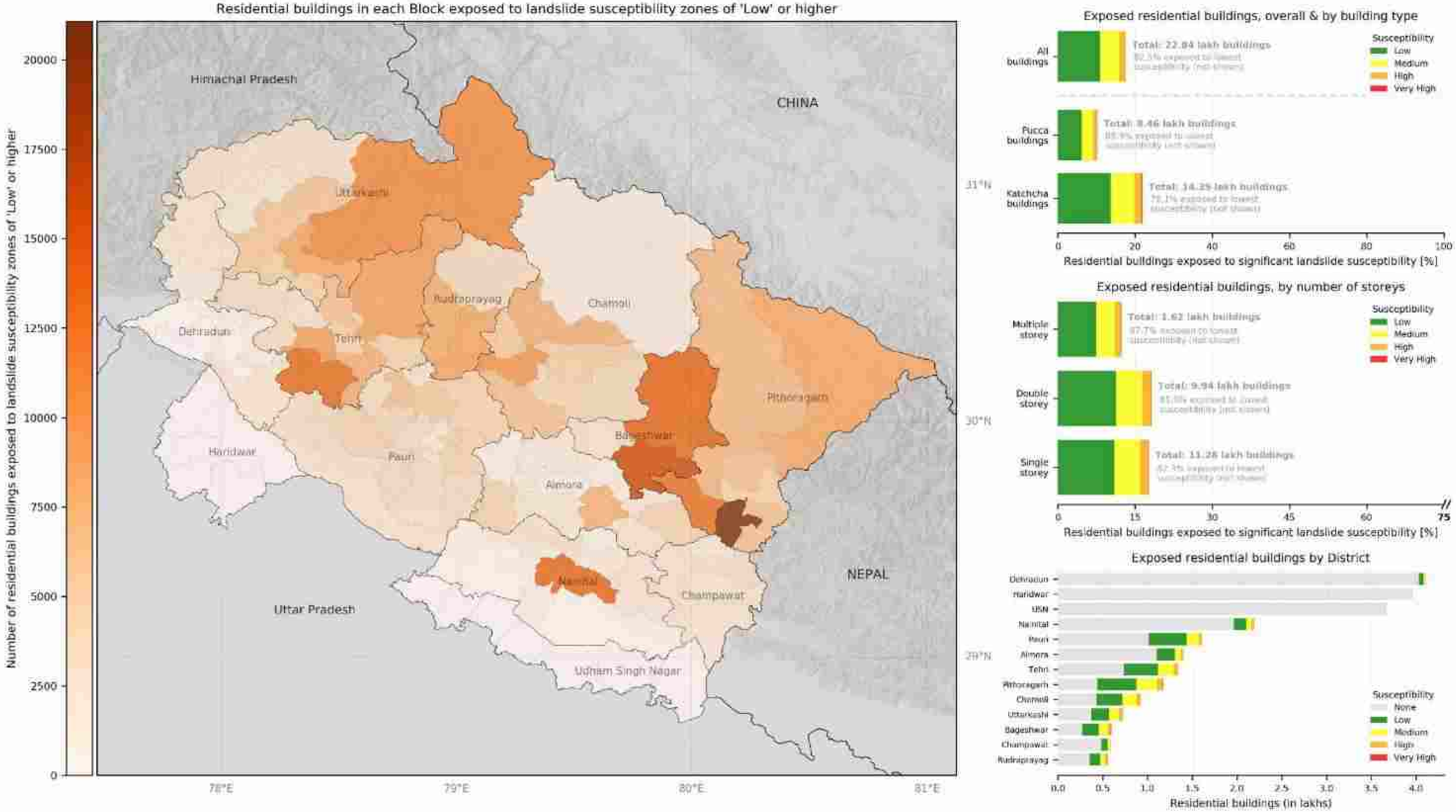

Figure 3.134: Visual summary of residential buildings exposed to landslide susceptibility zones

3.5.4 Critical building exposure to landslides

Figure 3.135 shows the exposure of critical buildings to the various landslide susceptibility zones. As illustrated in the plots, this portfolio is comprised of health facilities, educational institutions, fire/police stations and other government buildings.

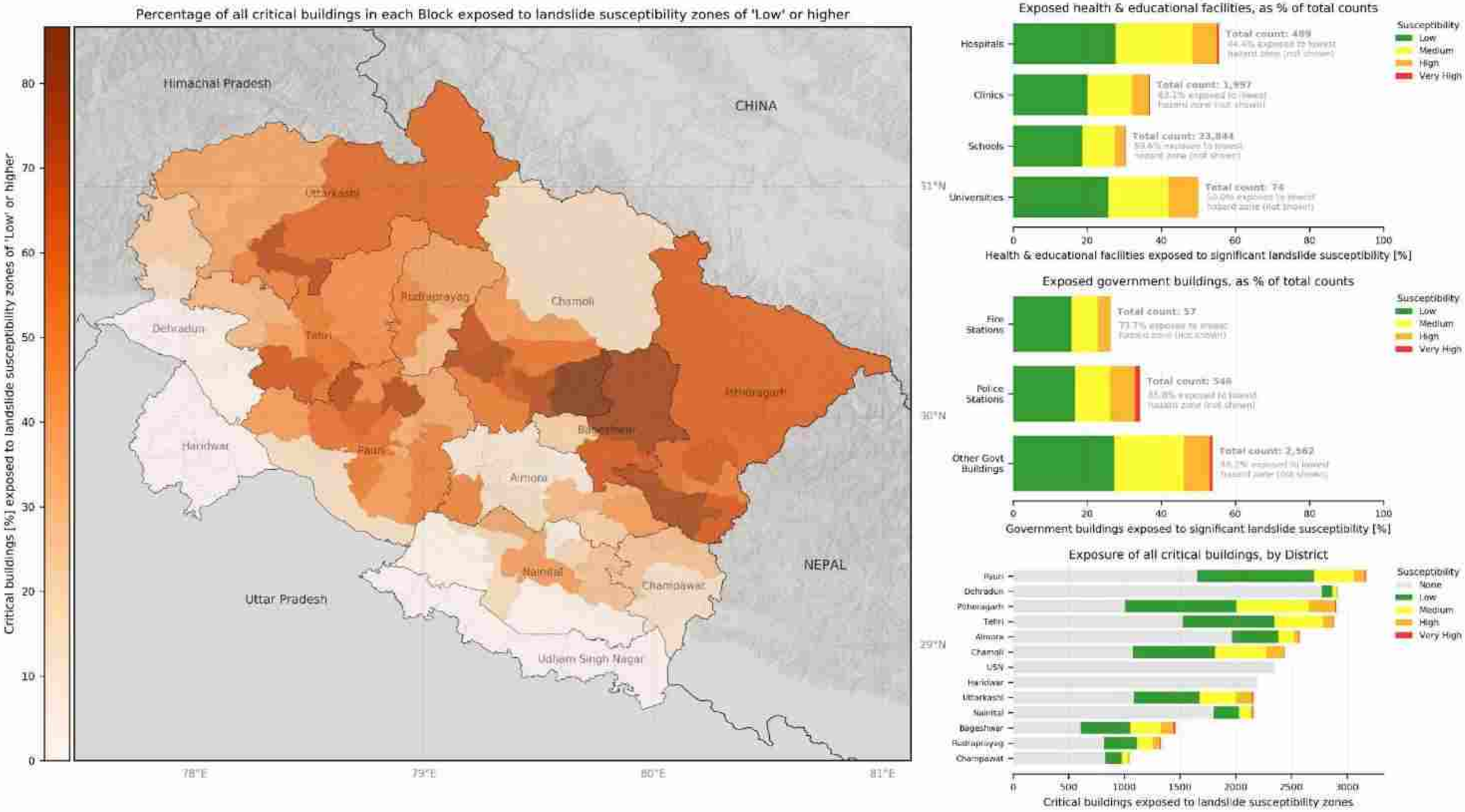

Figure 3.135: Visual summary of critical buildings exposed to landslide susceptibility zones

3.5.5 Transportation infrastructure exposure to landslides

Figure 3.136 shows the exposure of critical buildings to the various landslide susceptibility zones. As illustrated in the plots, this portfolio is comprised of road, rail and air infrastructure.

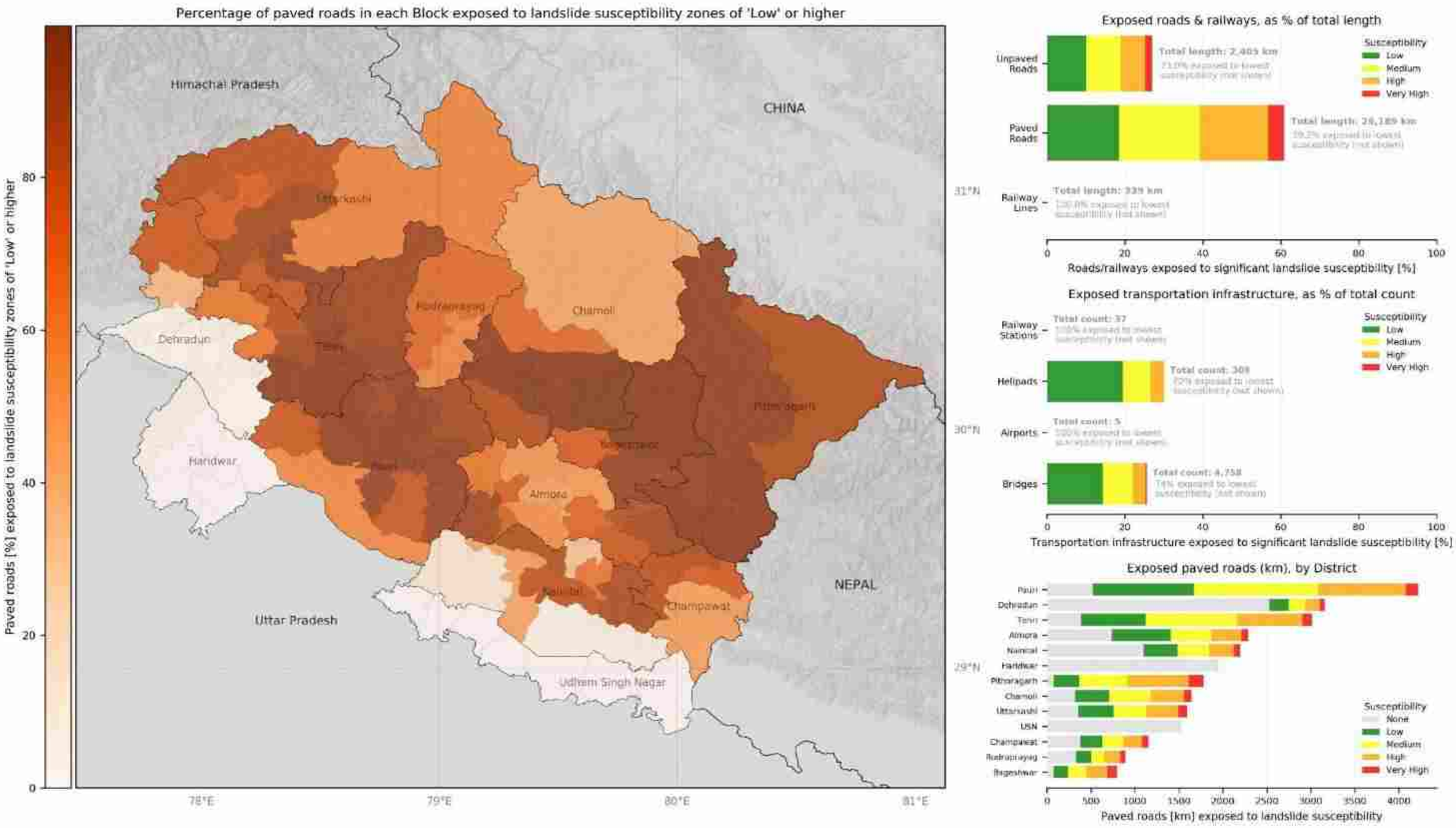

Figure 3.136: Visual summary of transportation infrastructure exposed to landslide susceptibility zones

3.5.6 Power infrastructure exposure to landslides

Figure 3.137 shows the exposure of power infrastructure to the various landslide susceptibility zones. As illustrated in the plots, this portfolio is comprised of substations (transmission and distribution), hydropower stations and dams.

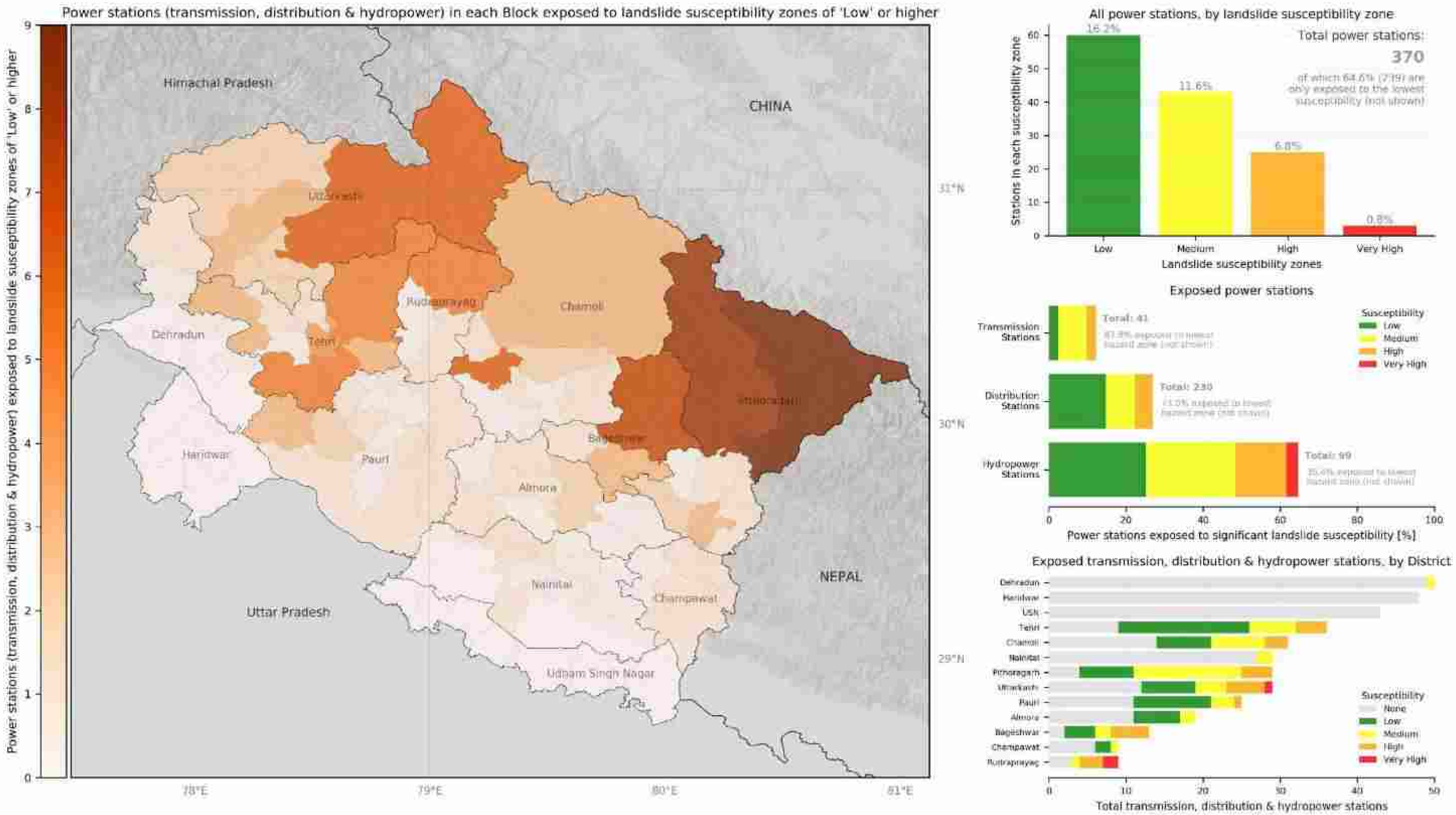

Figure 3.137: Visual summary of power infrastructure exposed to landslide susceptibility zones

3.5.7 Economic sector exposure to landslides

Figure 3.138 shows the exposure of agriculture (which includes equipment and other forms of capital investment) to the various landslide susceptibility zones.

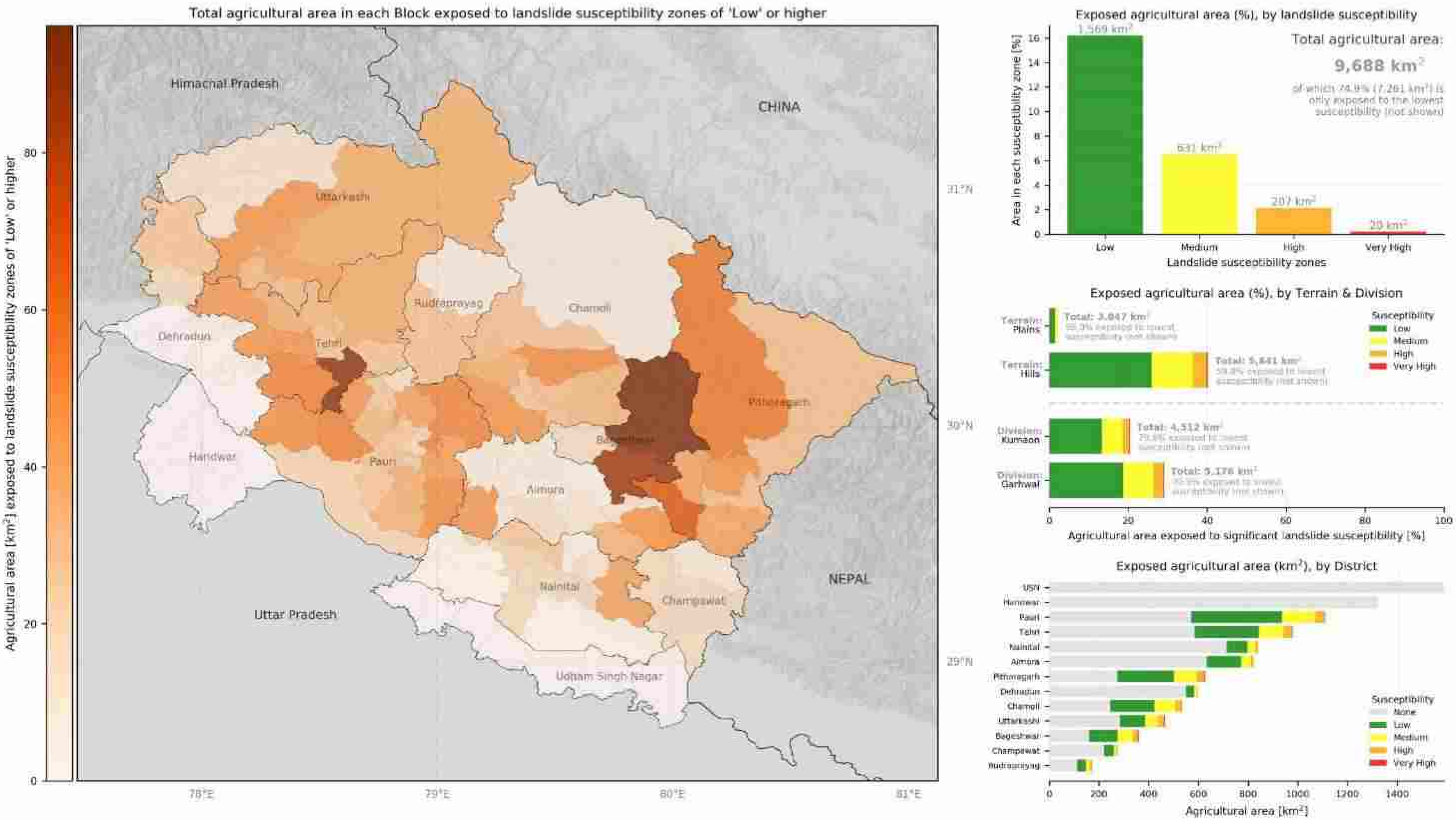

Figure 3.138: Visual summary of agriculture exposed to landslide susceptibility zones

Figure 3.139 shows the exposure of horticulture (which includes equipment and other forms of capital investment) to the various landslide susceptibility zones.

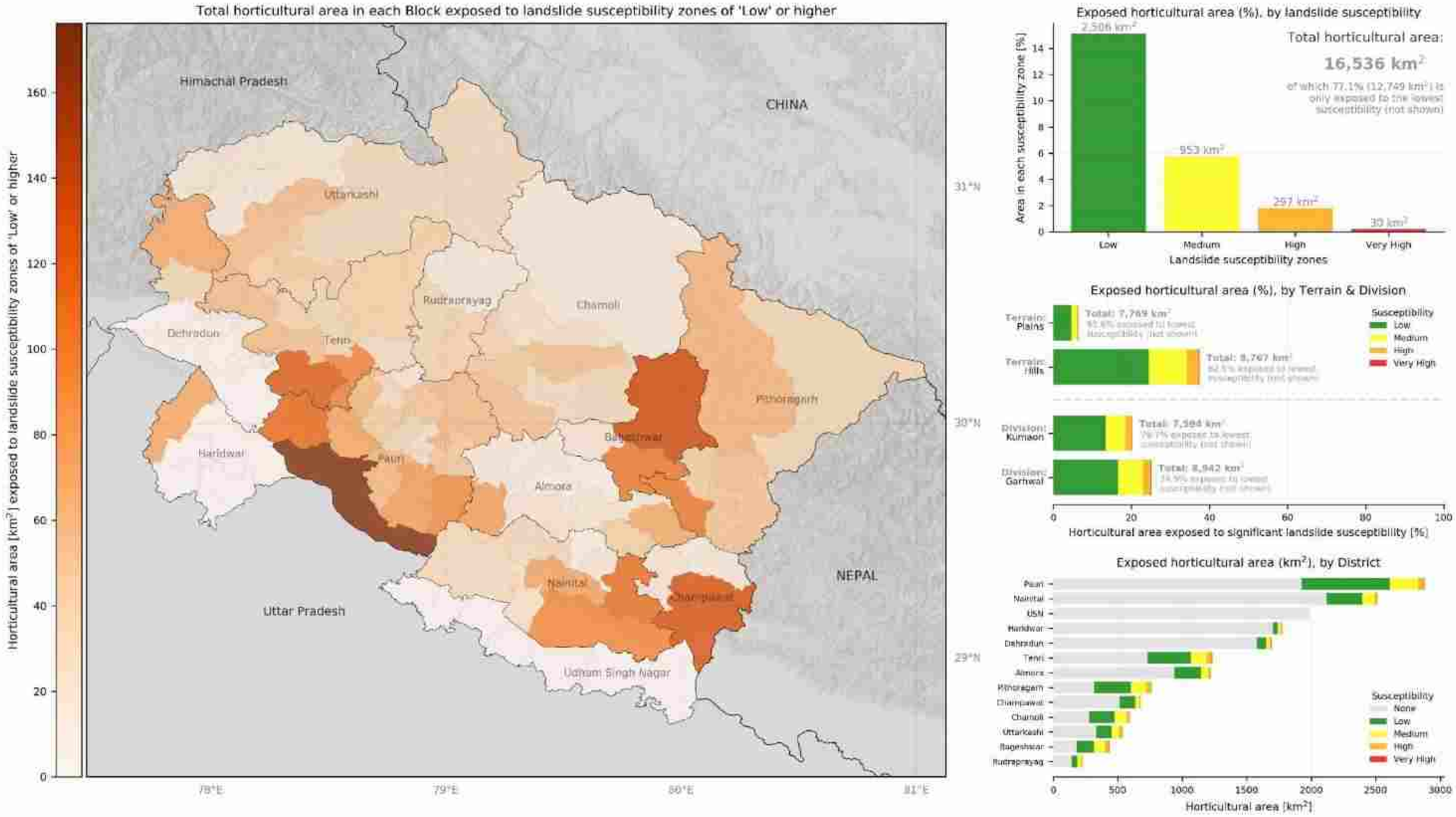

Figure 3.139: Visual summary of horticulture exposed to landslide susceptibility zones

Figure 3.140 shows the exposure of industry, commerce and mining to the various landslide susceptibility zones.

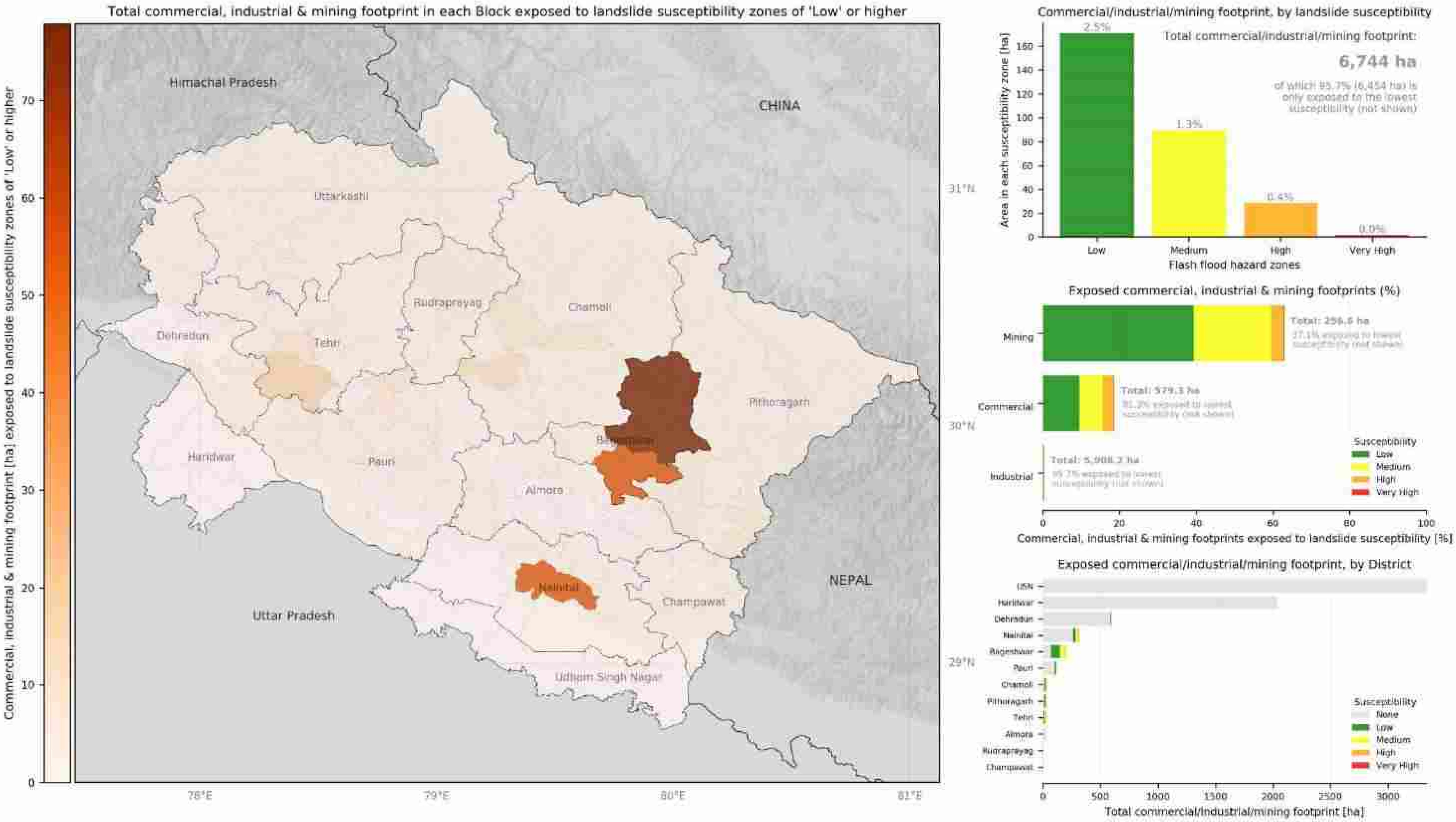

Figure 3.140: Visual summary of industry, commerce and mining exposed to landslide susceptibility zones

Figure 3.141 shows the exposure of potential tourism revenue to the various landslide susceptibility zones. (Note that the map's colour scale is not equally spaced, in order to visualise the full range of values – care should be taken when reading the highest class values).

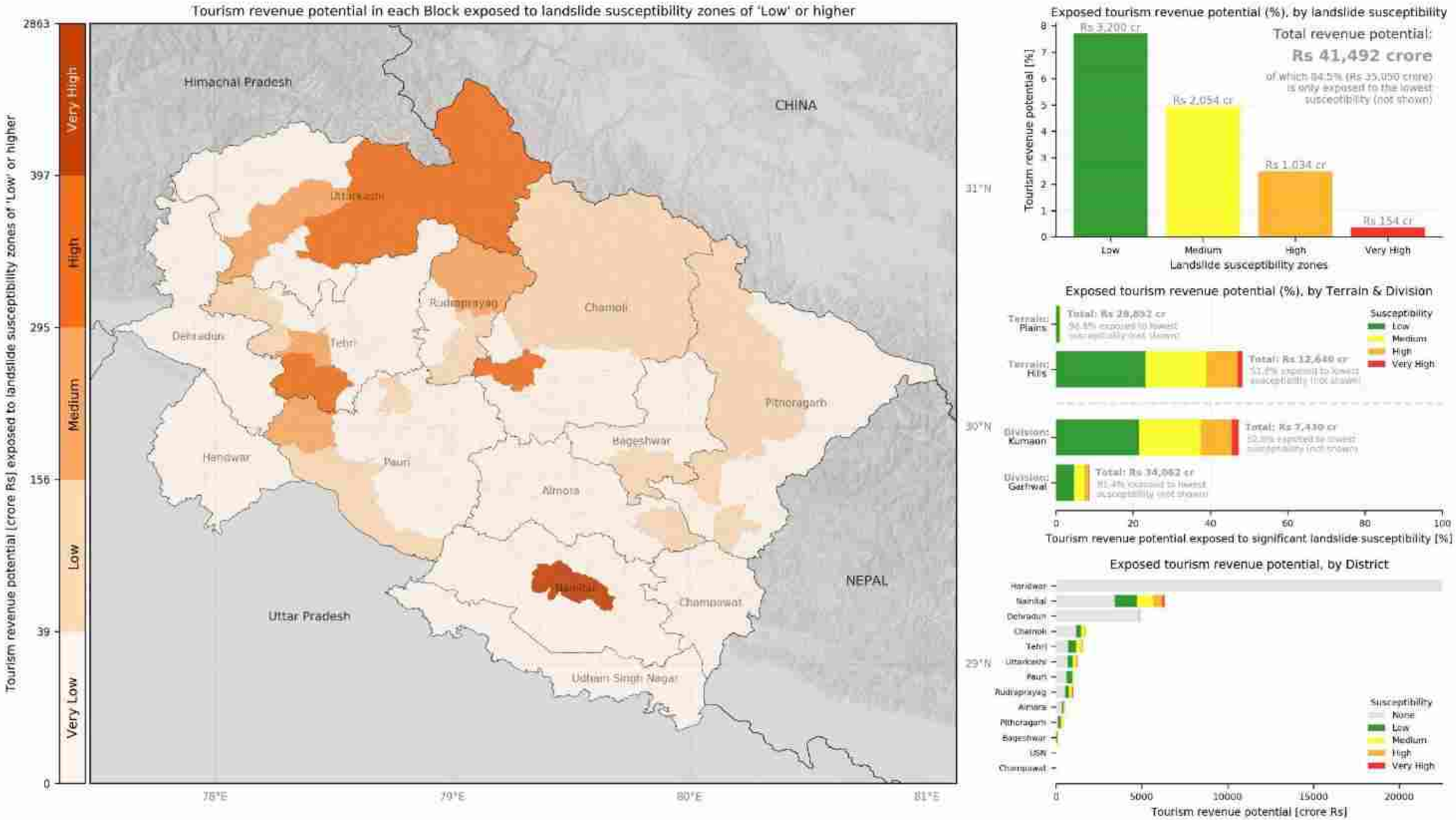

Figure 3.141: Visual summary of tourism revenue potential exposed to landslide susceptibility zones