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Tele-effect of geomorphological change on the spatial variability of the precision of SfM-MVS 3D point-cloud models

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ABSTRACT

Earth-surface processes research is increasingly using the SfM-MVS (Structure from Motion and Multiple-View Stereophotogrammetry) method to model land surface change over time at a very fine-scale. However, the role of topographic change on the error calculated from "stable and fixed" Ground Control Points is under-documented and as far as the authors are aware, it has not been evaluated as yet. Therefore, the present study is an analysis of the variability inherent to the SfM-MVS method used for 3D terrain modeling, in a semi-controlled environment, comparing repeats of measurements, and repeats including topographic change in the laboratory scene, in order to assess the role of elevation change in the scene on the space that remains unchanged. The methodological framework involves varying the terrain morphology by adding 50 and 100 ml of sand to an originally horizontal sandbox, creating a mount in the centre. Then, the authors compared the different experimental surfaces and their repeats acquired by SfM-MVS, and using Gaussian Kernel Density Estimation (KDE). Results demonstrated that under stable and uniform flat surface conditions, the SfM method yields relatively consistent results (standard deviation variety less than 0.027 mm). However, when the experiments included the 50 ml and 100 ml mount of sand, the variability between repeats increased, even for location where no topographic change had occurred. The authors argue that the topographic variability is spreading the error, increasing it compared to the flat experiment. By extension, this consideration is essential, especially for research investigating topographic change such as landslide and other erosion and deposition processes, because the error propagation varies with the surface change, and relating erosion/deposition to topographic change needs to be done carefully.

KEYWORDS

geomorphologic change; point cloud; structure from motion; precision variability; terrain modeling

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1. Introduction

Within a decade or so (Fonstad et al. 2013; Gomez 2012, 2013; James and Robson 2012; Westoby et al. 2012), SfM-MVS (Structure from Motion – Multiple View Stereophotogrammetry) has deeply transformed the fields of geo-sciences interested in constructing "precise objects' morphology" for a "low-cost", as it offers high spatial density measurement for potentially extensive areas.

The SfM-MVS method enables the reconstruction of three-dimensional spatial models from a series of overlapping two-dimensional images (Szeliski 2010). This technique has been widely applied to various fields outside geosciences as well: e.g. archaeology (de Reu et al. 2013, 2014; Verhoeven 2011), terrain surveying, and robotic navigation (Hixon et al. 2018; Deliry and Avdan 2021; Saputra et al. 2018). In combination with the rapid advancement of Unmanned Aerial Vehicle (UAV) technology, SfM-MVS has been particularly instrumental in geosciences for the production of DEMs (Digital Elevation Models) and DSMs (Digital Surface Models). Furthermore, UAVs also allow the access to previously difficult or unreachable areas (e.g. Gomez 2023; Hayakawa et al. 2020). Consequently, SfM-MVS has been applied to a wide range of environment from the bottom of the ocean to the mountain tops: submarine morphology (Lockhead and Hedley 2022; Qiao et al. 2019), coastal morphology (e.g. Clark et al. 2021; Gomez et al. 2023; Hayakawa et al. 2020), floodplain analysis (e.g. Bakker et al. 2017), mountainous terrains (e.g. Bi et al. 2023), and volcanic landscapes (Gomez 2014; Gomez et al. 2022), including the reconstruction of vegetation and trees (Morgenstern and Gomez 2014).

Because of its low cost and versatility, the method has also been extensively employed to depict topographic variations over time, in order to quantify fast-evolving landscapes. Among other examples, SfM-MVS has been particularly useful to quantify the dynamic of mountain landslides (Mauri et al. 2021; Peppa et al. 2018) and coastal landslides (Esposito et al. 2017), coastal dunes' erosion and deposition (Mestre-Runge et al. 2023), as well as gully erosion and deposition where seasonal to yearly change are important (Tsunetaka et al. 2021; Gomez et al. 2021). The comparisons between the different time-steps are either been done at the pointcloud level (Lague et al. 2013; Esposito et al. 2017) or at the DEM level (e.g. Mauri et al. 2021), using vertical matching of the data.

To work across spatial scales and repeated surveys, error analysis is essential, and so is the georeferencing against ground control points (GCPs), especially for repeated surveys (Forlani et al. 2018). But, even with GCPs' constraints, Liu et al. (2022) noted a variability in the produced point-clouds even under identical conditions. One of the challenges is due to the multiple sources of error. It includes influences from the terrain itself, inaccuracies due to the camera or the lens characteristics, as well as computational errors (Westoby et al. 2012; Deliry et al. 2021). Notably, many studies tend to investigate error as a bundled dataset, while there is still a need to separate the influence of different parameters on the error. This is of particular importance, because the use of SfM-MVS is often motivated by its potential high-precision (Iheaturu et al. 2020; Panagiotidis et al. 2016). Accordingly, geoscientists have developed several methods to test the precision of different models, notably with the increased use of UAVs for DEMs' construction (Tab. 1).

Tab. 1 Accuracy Evaluation Studies in UAV Photogrammetry and SfM.

Environment	Evaluation Criteria	Error or Conclusion	Reference
Sandy coastal topography via UAV	Vertical accuracy, compared with GCPs	0.09–0.11 m	Long et al. (2016)
Riverbed topography	Mean error/standard deviation, compared with GCPs	0.016–0.089 m / 0.065–0.085	Woodget et al. (2015)
Snow depth RMSEs	RMSE of depth of snow on rocks/grass, compared to manual probe measurements	0.07–0.15 m / 0.3m	Bühler et al. ; Gindraux et al. (2016/2017)
Landslide monitoring RMSEs with UAVs	Horizontal/vertical RMSE compared with GCPs	0.07 m, 0.06 m	Lucieer et al. (2014)
Terrain models in moraines (UAV)	RMSE, compared with GCPs	0.2 m, 0.59 m in dense vegetation	Tonkin et al. (2014)
UAV-SFM accuracy test in flat areas	MSE in X, Y and Z coordinates, compared with GCPs	20.93 mm, 18.48 mm and 46.05 mm	Iheaturu et al. (2020)
UAV-SfM in fluvial channels	Sediment volume estimation, compared with terrestrial laser scanning	Effective for sediment changes	Tsunetaka et al. (2020)
UAS-SfM accuracy vs traditional methods	Factors impacting UAS-SfM accuracy	Accuracy mainly depends on sensor resolution, flight height, image overlaps, and the number, distribution, and accuracy of GCPs	Deliry et al. (2021)
Accuracy of UAV-SFM on farmland with vegetation	Vertical RMSE, compared with GCPs	approximately 10cm	Peppa et al. (2016)

Despite these advances, the inherent error due to the repeat of topographic modelling using SfM-MVS still needs further research (Zhao et al. 2021).

Therefore, out of a broad set of potential issues (lighting, seasonality, reflectance and color of the target, position of the camera, etc.), in this contribution the authors propose to investigate (1) the variability among repeats and (2) the role of topographic variation on the error generated by repeats, notably because the spatial error propagation is a well-known phenomenon in photogrammetry, which is arguably affecting the results of multiple SfM-MVS models.

2. Methodology

The authors propose to reach the goal mentioned above, by using a controlled environment (single-color sand, controlled lighting) in order to derive a model of precision (the accuracy component of the error is difficult to reach, as for most SfM-MVS models in geomorphology, because the real shape measured is not perfectly known), as for complex targets found in the natural environment, it is difficult to define a benchmark measure of object, and error can be approached from the variability of precision between the repetition of the same measure.

The methodology of the present contribution is based on the repeated SfM-MVS measurements (Fig. 1) of an unvarying surface based on the following experimental procedure, to which two generations of sand mount were added to produce three generations of experiments.

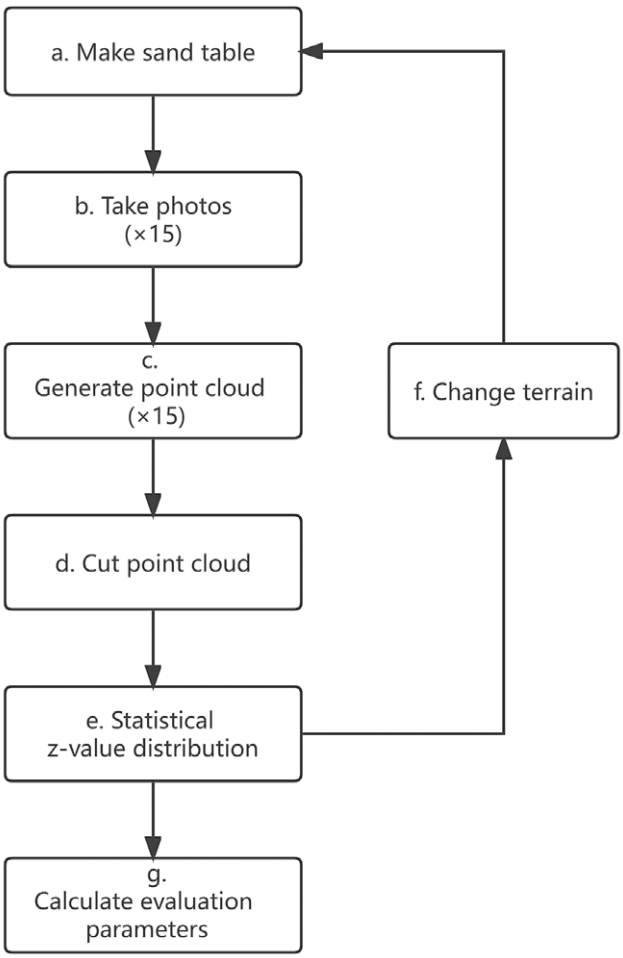


Fig. 1 Point cloud generation and analysis process.

2.1 Material, data acquisition and 3D model construction

For the present research, a sandbox model was crafted using acrylic plates and double-sided tape on which a single layer of calibrated 0.5 mm yellow color silicates covers the surface. This allows the experimental setup to have a regular roughness and surface height. The experiments include (a) one set of experiments using the flat surface, then (b) a set of experiments with a conical mount made of 50 ml of sand poured in the center of the experimental model, and finally (c) a set of experiments with a sand cone of 100 ml in the centre. Each set of experiments is made of 15 repetitions of the same measure, and each of the 15 repetitions was captured using 45 to 50 photographs using a Ricoh camera (Tab. 2).

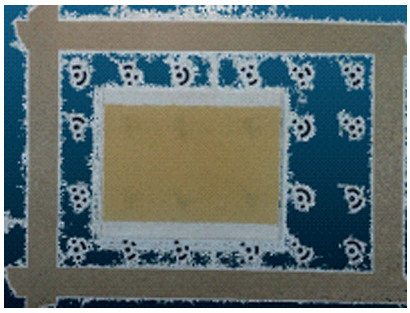
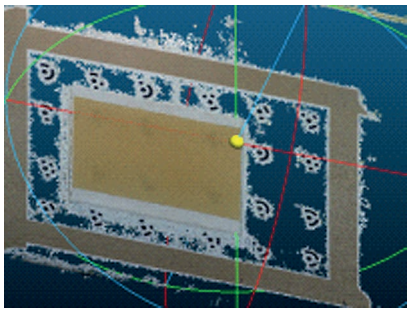
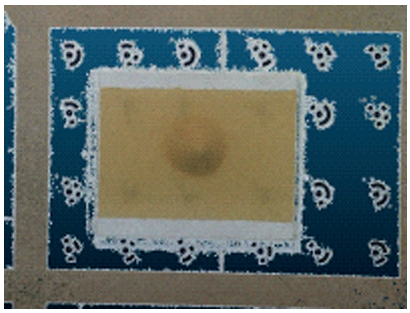
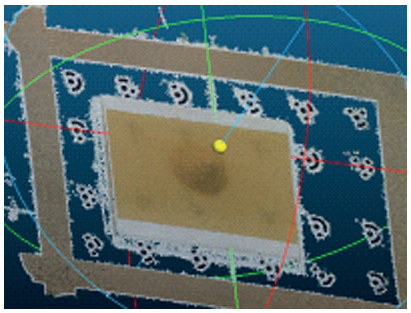
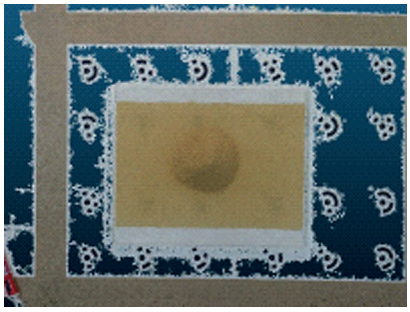
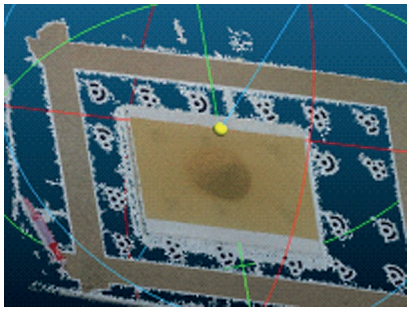
Each set of photographs was then processed using the SfM-MVS algorithm in Metashape-Pro® (Agisoft©) to generate the point cloud data (e.g. Tinkham et al. 2021; Catala-Roman et al. 2024). The processing started from a sparse point-cloud reconstruction and then a dense point-cloud reconstruction, and the registration of the pointcloud was done using the targets that can be automatically recognized (cf. Tab. 3).

Tab. 2 The equipment and software used in the experiment.

Sand Table	Base	Acrylic Board + Double-sided Tape	
	Sand	0～100 ml Yellow Sand	
GCP	18 Marks from Metashape		
Camera	Main Body	RICOH WG-7	
	Lens	RICOH DW-5 171930*	
	Pixel	5184 × 3888	
Computer	DELL G15 5520	CPU	12th Gen Intel(R) Core(TM)i7-12700H 2.30Ghz
		GPU	NVIDIA GeForce RTX 3060 Laptop 8G
		RAM	16GB 4800Mhz
Soft	Generate Point Cloud	Metashape	
	Processing	Python	
Camera Position	Shooting height	45 ± 3cm	
	Tilt	< 10% taken as Nadir	

* Additional lenses to eliminate distortion caused by camera lenses (Wang et al. 2008; Wang et al. 2022).

Tab. 3 Examples of point clouds generated from different volumes of sand.

Sand volume	Top view	Tilt view
0 ml		
50 ml		
100 ml		

After cropping all the points outside the experimental table covered with yellow sand, the number of points generated for each experiment is on average ~800,000 points, with a maximum of 1,012,235 points and a minimum of 710,705 points generated for the experiments using the flat surface only. For the experiments with a sand cone of 50ml, the number of points is on average of 930,000 points, with a maximum of 1,139,308 points and a minimum of 794,791 points. Finally, the pointclouds for the experiments with the 100 ml sand cone displays an average points' numbers of 1,000,000 points, with a maximum of 1,265,351 points and a minimum of 874,874 points.

2.2 Data Analysis and statistical simulation

Subsequently, Python was employed to segment the point cloud data, perform counts, and compute the different statistical parameters to assess variability. For this purpose, the point cloud data was then divided into a 5 × 8 grid cells, so that the Z-values in each grid cell was handled as statistical populations, for which distribution functions were created to compare the different locations on the cell (Fig. 2).

Then for each grid cell, the authors calculated distribution of the Z-value and determine the distribution function using the distribution peak and its

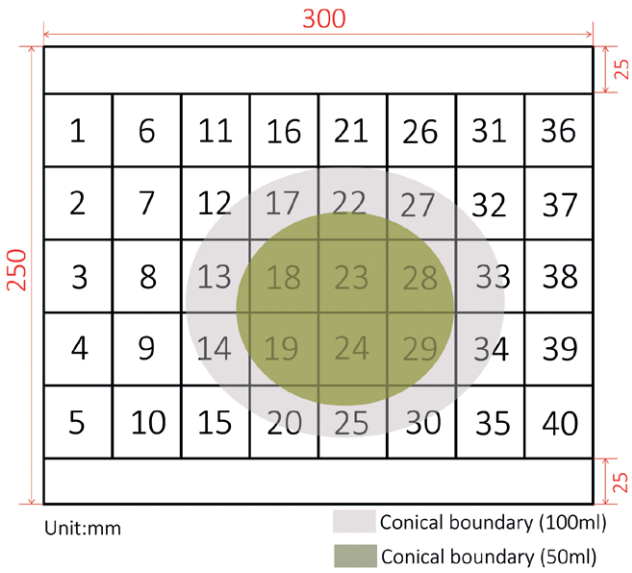


Fig. 2 Grid cells division of sand table (in the result section, the cell number refer to the numbers in this table).

position (peak-z), the left and right tails (labelled Min-z and Max-z), the full width at half-maximum (FWHM), and the interquartile spacing (IQR). The distribution of the Z-values was then computed using the Gaussian Kernel Density Estimation (KDE) method (Zaman et al. 2017). KDE is a non-parametric method employed for estimating the Probability Density Functions (PDF):

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \quad (1)$$

where $\hat{f}(x)$ represents the estimated density at point x, and $x_1, x_2, \ldots, x_n$ are the sample points, K is the kernel function, and is the bandwidth. This method has been used to analyze the spatial distribution characteristics of point cloud data for 3D modeling, 3D object recognition, and 3D model registration (Zhang et al. 2021), especially when datasets have varying resolutions and qualities (King et al. 2016; Vestal et al. 2021), which was estimated to be one of the working assumption for the present study as the average number of points varied between the different types of experiments.

Because the objective of the present study is to investigate the spatial variability of the error in seemingly unchanging surface, the distribution function of each grid-cell was analysed separately. To provide a synthetic view of the points, the peak horizontal coordinate (Peak-z), the minimum Z-value (Min-z), the maximum Z-value (Max-z), the Full Width at Half Maximum (FWHM), and the Interquartile Range (IQR) were used as statistical markers (cf. summary Tab. 4).

Tab. 4 Evaluation parameters.

Parameter	Calculation Method	Remarks
Peak-z	–	The horizontal coordinate of the vertex in the z-value distribution function.
Min-z	–	Represents the lowest value in the distribution, indicating the lower limit of Z-values.
Max-z	–	Represents the highest value in the distribution, indicating the upper limit of Z-values.
FWHM	$FWHM = x_r - x_l$	Describes the width of the distribution defined as the width at which the function value reaches half of its maximum value. Here x_r, x_l, are the horizontal coordinates on the distribution curve where the function value reaches half of the maximum on the right and left sides, respectively.
IQR	$IQR = Q_3 - Q_1$	A statistical measure describing the dispersion of a distribution representing the range of the middle 50% of the data. Where Q_3 is the third quartile (75th percentile), and Q_1 is the first quartile (25th percentile).

3. Results

Using the same acquisition method on the same surface several times is showing an expected variability in the elevation. Furthermore, on a seamlessly homogeneous surface, this variability shows spatial dependence. The results of the experiments show the greatest variations for experiments Y0-1 to Y0-15 using the flat 10 mm thick plate (Tab. 5), the peak values of Z ranged over 0.117 mm, averaging between 10.84 mm and 10.96 mm, with the greatest difference observed in grid cell 1 (detailed results for each cell of each experiment are provided in the appendix).The difference in the maximum values varied between 0.072 mm and 0.341 mm in 15 replicates. The difference in Min-z values ranged from 0.068 mm to 0.206 mm, with an outlier value of 9.627 mm in grid cell 21 removed, and the average min-z value for the same grid cell was 10.574. The Max-z values ranged between 10.813 mm and 11.154 mm, with grid cell 35 showing the greatest variation. FWHM values extended from 0.19 to 0.286, and grid cell 27 displayed the largest variability. The IQR spanned from 0.102 to 0.148, with grid cell 27 also exhibiting the most distinct differences. The extent of variability across these measurements is evidence in the statistical indicators of Peak-z, Min-z, Max-z, FWHM, and IQR (Tab. 5).

For the experiments where the surface is "flat", the changes of Peak-z, FWHM and IQR were not significant. (Tab. 5). However, within each experiment, the variability of the minimum and maximum value can vary by about 10% (e.g. Y0-8 in Tab. 5).

Tab. 5 Z-value distribution of point cloud with the cells where the largest variability was observed for the flat environment (i.e. no extra-sand added).

	Peak-z	Min-z	Max-z	FWHM	IQR
	Cell-1	Cell-21	Cell-35	Cell-27	Cell-27
Y0-1	10.848	10.584	10.970	0.190	0.102
Y0-2	10.933	10.601	10.892	0.227	0.122
Y0-3	10.964	10.565	10.842	0.239	0.126
Y0-4	10.897	10.544	10.904	0.230	0.119
Y0-5	10.923	10.571	10.935	0.215	0.114
Y0-6	10.940	10.525	10.813	0.238	0.128
Y0-7	10.919	10.490	10.876	0.237	0.126
Y0-8	10.939	9.627	11.154	0.238	0.125
Y0-9	10.953	10.635	10.834	0.217	0.115
Y0-10	10.936	10.617	10.978	0.200	0.109
Y0-11	10.921	10.646	10.885	0.254	0.131
Y0-12	10.915	10.603	11.061	0.264	0.138
Y0-13	10.919	10.542	10.952	0.286	0.148
Y0-14	10.893	10.577	10.957	0.231	0.119
Y0-15	10.916	10.530	10.895	0.227	0.120
Difference	0.117	1.019	0.341	0.096	0.047

Overall, the precision is decreasing when the topography becomes more complex (i.e. with the central conic pile of sand). For the scenario where 50 ml of sand was added, the Peak-z values for Y50-1 to Y50-15 ranged from 18.783 to 19.494, with grid cell-1 showing the most significant differences. Min-z values oscillated between 10.094 and 10.673, with the largest variations in grid cell-36. Max-z exhibited a range from 18.553 to 18.833, with grid cell-35 displaying the most noticeable variability. FWHM varied from 12.411 to 12.950, with grid cell-27 having the most pronounced differences. The IQR extended from 7.063 to 7.223, with the greatest variability again observed in grid cell-27. These data points highlight the impact of added sand on the variability of the measurements (Tab. 6).

The second set of experiments revealed a significant increase in the variability of the SfM method, particularly in the Peak-z parameter, which exhibited the most notable variability. The Peak-z variability substantially increased, showing a deviation of 0.711 mm. This heightened variability may be attributed to changes in the surface morphology of the sandbox, resulting in greater uncertainty in the SfM method when measuring similar features. While the variability in FWHM and IQR is lower compared to the experiments without added sand, it still shows some increase. Furthermore, the variability of Min-Z increased, but the variability of Max-Z decreased slightly. In this scenario, a change in the Peak-z of the distribution function is observed, while the shape of the curve displays smaller variations.

Upon adding 100 ml of sand (Tab. 7), the dataset (Y100-1 to Y100-15) showed Peak-z values ranging from 22.959 to 23.451, with grid cell-1 exhibiting the most variability. Min-z ranged from 10.495 to 10.727, with the most significant differences in grid cell-36. Max-z values varied between 19.305 and 19.628, with grid cell-35 showing the greatest range of variability. FWHM was observed to range from 16.870 to 17.351, with the largest differences in grid cell-27. The IQR varied from 5.472 to 5.619, with the most variability again noted in grid cell-27.

With the addition of 100 ml of sand, the variability in Peak-z remains relatively high but is reduced compared to the 50 ml sand addition. Despite the increased volume of sand, the complexity of the surface shape does not increase correspondingly. This may suggest that the SfM method can achieve more stable results for larger targets. The continued low variability in FWHM and IQR also indicates that the shape of the distribution function undergoes minimal change.

Even for the grid cells that do not display any significant change, the variability of the Z values is changing in between experiments. The presence of the 50 ml and then 100 ml sand cone is impacting the variability of grid cells where the sand cone is not located (Fig. 3). The cells the further away from the cone are grid cells cell-1, cell-5, cell-36 and cell-40, and the spread of the z-values as well as the position (mean, minimum and maximum) are all changing significantly (Fig. 3). The peak value of cell 1 first increases and then decreases, from experiments Y0 to Y50 to Y100, while the spread of the measurements decreases. The peak position of

Tab. 6 Z-value distribution of point cloud and the cell of the largest difference: 50 ml.

	Peak-z	Min-z	Max-z	FWHM	IQR
	Cell-29	Cell-6	Cell-20	Cell-28	Cell-25
Y50-1	19.110	10.614	18.741	12.411	7.134
Y50-2	19.144	10.647	18.754	12.606	7.223
Y50-3	19.072	10.591	18.697	12.579	7.117
Y50-4	18.945	10.630	18.742	12.508	7.075
Y50-5	19.131	10.094	18.685	12.602	7.161
Y50-6	19.343	10.612	18.661	12.728	7.063
Y50-7	19.037	10.629	18.833	12.617	7.145
Y50-8	19.126	10.550	18.751	12.570	7.139
Y50-9	19.022	10.545	18.726	12.577	7.170
Y50-10	19.494	10.576	18.565	12.950	7.139
Y50-11	19.437	10.673	18.715	12.641	7.163
Y50-12	19.012	10.601	18.704	12.681	7.185
Y50-13	19.339	10.576	18.684	12.698	7.159
Y50-14	19.228	10.439	18.553	12.813	7.141
Y50-15	18.783	10.526	18.671	12.571	7.119
Difference	0.711	0.578	0.280	0.539	0.160

Tab. 7 Z-value distribution of point cloud and the cell of the largest difference: 100 ml.

	Peak-z	Min-z	Max-z	FWHM	IQR
	Cell-19	Cell-37	Cell-27	Cell-18	Cell-20
Y100-1	23.257	10.677	19.383	16.870	5.530
Y100-2	22.959	10.624	19.420	17.189	5.502
Y100-3	23.152	10.575	19.461	16.874	5.501
Y100-4	23.159	10.643	19.445	16.992	5.543
Y100-5	23.168	10.603	19.511	17.084	5.577
Y100-6	23.084	10.495	19.305	16.904	5.503
Y100-7	23.327	10.590	19.476	17.351	5.576
Y100-8	23.110	10.637	19.373	16.867	5.483
Y100-9	23.114	10.645	19.583	16.935	5.486
Y100-10	23.092	10.685	19.463	17.037	5.552
Y100-11	23.034	10.623	19.440	17.019	5.524
Y100-12	23.451	10.641	19.495	17.283	5.472
Y100-13	23.097	10.625	19.417	17.032	5.541
Y100-14	23.230	10.727	19.628	17.099	5.524
Y100-15	23.105	10.632	19.437	17.142	5.619
Difference	0.492	0.232	0.322	0.484	0.147

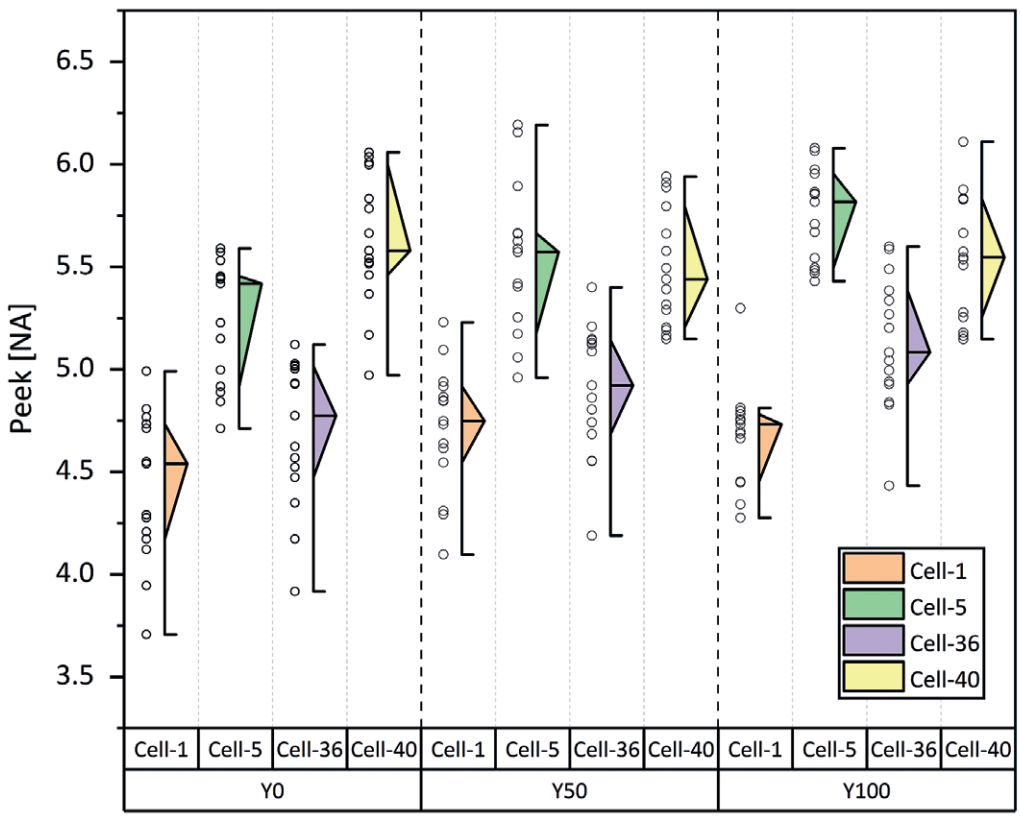


Fig. 3 Spatial Variability of the Z-Peak Values. The magnitude of the peak indicates the concentration of the data. The variation in the width of the peak distribution indicates changes in variability. Significant differences are observed even in areas without topographical changes, such as in Cell-1 and Cell-5. Furthermore, these variations exhibit different trends at different locations.

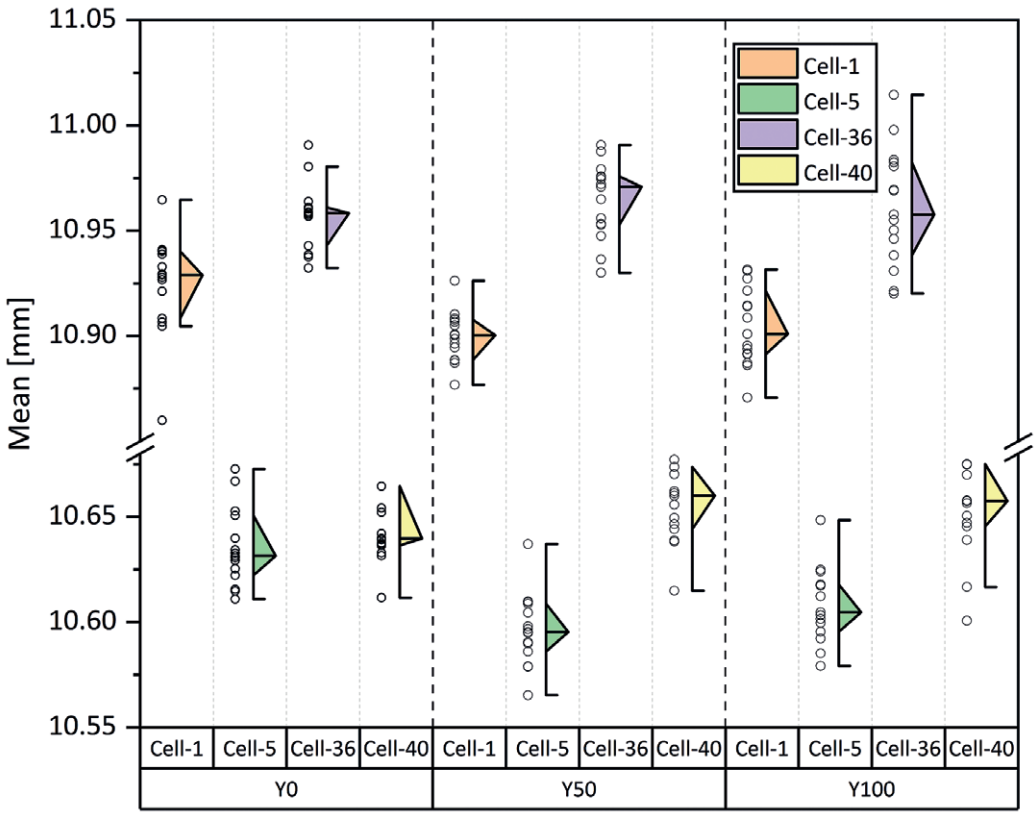


Fig. 4 Spatial Variability of Distribution Mean Values of Z. Variations in the mean suggest that the overall cell is influenced by topographical changes. Fluctuations are significant at various locations, with the changes in Cell-36 being particularly notable, demonstrating higher instability.

cell-5 increases, and the dispersion first increases and then decreases. The peak value of grid 36 is larger, but the dispersion is basically unchanged. Finally, the peak of the cell 40 grid decreases slightly and instead becomes more dispersed (Fig. 3).

For the same cell, the mean fluctuates somewhat, but the degree of dispersion is basically the same (Fig. 4). The mean decreased in Cell-1, and slightly increased in Cell-5 in Y-100, and their degree of dispersion remained basically unchanged. Cell-40 is stable, but the dispersion of Cell-36 increases significantly.

When the spatial distribution and repeated measurements are displayed together, the differences between cells can be significantly observed. Calculate the standard deviation of the remaining cells after removing the area that the sand will cover. In Fig. 5-a, cell-1, cell-2, and cell-6 show large standard deviations, and several positions in the 8th measurement show large standard deviations. After the addition of 50 ml sand, the standard deviation of each cell decreased, but cell-1 and cell-2 were still significantly higher than other positions (Fig. 5-b). When 100 ml of sand was added, higher standard deviations were observed for cell-1, cell-2, and cell-26 (Fig. 5-c). In general, the change of terrain does lead to different degrees of variation in the standard deviation of each location. From this representation of the data, one can see that the standard deviation of the points in each cell can vary, and so within a single set of experiments, with two corner locations showing consistently the highest standard deviation. Moreover, the increased in standard deviation does not seem to be related to the repeats themselves, as the variability is moving in space rather than just in between repeats.

4. Discussion

4.1 Summary of the main findings

In the present contribution, the authors have added to the already known issue of error in SfM-MVS measurement of the land surface a spatial dimension, showing that the error can be location dependent. This finding is consistent with previous studies that have reported spatial variability in SfM-MVS accuracy (James and Robson 2012; Fonstad et al. 2013; Smith and Vericat 2015). Furthermore, the steeper the terrain, the larger the error. This phenomenon is already notably known, with problems such as doming effects and increase of the topographic maxima (James and Robson 2014; Javernick et al. 2014; Eltner et al. 2016). However, the novelty of the present contribution shows that flat surfaces close to areas with high topographic variability also experience an increased error. In previous work, Gomez et al. (2015) found that the SfM measurement over forested canopy was in the range of 10 m at the landscape scale, but the author did not consider the spatial diffusion of this error to other areas, and it is most likely that this error diffused in other areas, as a function of the elevation variability as shown in the present results.

4.2 Importance of the results for repeated measurements

This "tele-connection" of surrounding features on the error on "flat surfaces" is particularly important for research involving the repetition of measurements over time, in order to measure land deformation (Cucchiaro et al. 2020; Hemmelder et al. 2021). Indeed, it cannot be expected that the error will remain the same at a control point, event if it is known to be stable as long as other parts of the landscape are changing. It is thus important to reconsider this point for the measure of for instance: from coastal erosion (e.g. Fabris et al. 2021; Terefenko et al. 2018) and coastal sand-dune evolution (e.g. Gomez et al. 2024) to the evolution of volcanic gullies at mid- (e.g. Tsunetaka et al. 2021) to longer-term (e.g. Gomez et al. 2014), including the built-environment (e.g. Wei et al. 2021 for urban surface displacement). This observation can be further extended when surveying is conducted at different periods of the years (e.g. Micheletti et al. 2015; Groos et al. 2019; Niederheiser et al. 2021), as the vegetation growth and geometry change will modify the whole geometry of the scene.

4.3 Error "tele-connection" and surrounding morphology

The present experimental work has been investigating the variability in measured vertical values (topography for instance), using a regular flat surface, made of only one grain-size and one color, and two other surfaces with a central sand cone. As expected, the error varies from one repeat to another almost randomly, but the most important result is the "tele-connection" of the error when a spatially disconnected morphology change. In other words, surrounding geometries can influence a surrounding flat surface. In term of geomorphology a volcanic structure growing, or a landslide moving over a terrain has the potential to modify the error at target locations that are not subject to movement or any change.

Similar observations were made by Dr. Tsunetaka when he was preparing one of manuscript on Unzen Volcano (Tsunetaka et al. 2021). He stated that Ground Control Points were leading to different spatial spread of the error depending on the position of the Ground Control Point, especially in relation with the surrounding topography (private communication). In other words, topographic variability in the vicinity of one or a set of control points can lead to a change in the error at the control points, showing a similar "teleconnection" between surrounding features and the points on a flat area.

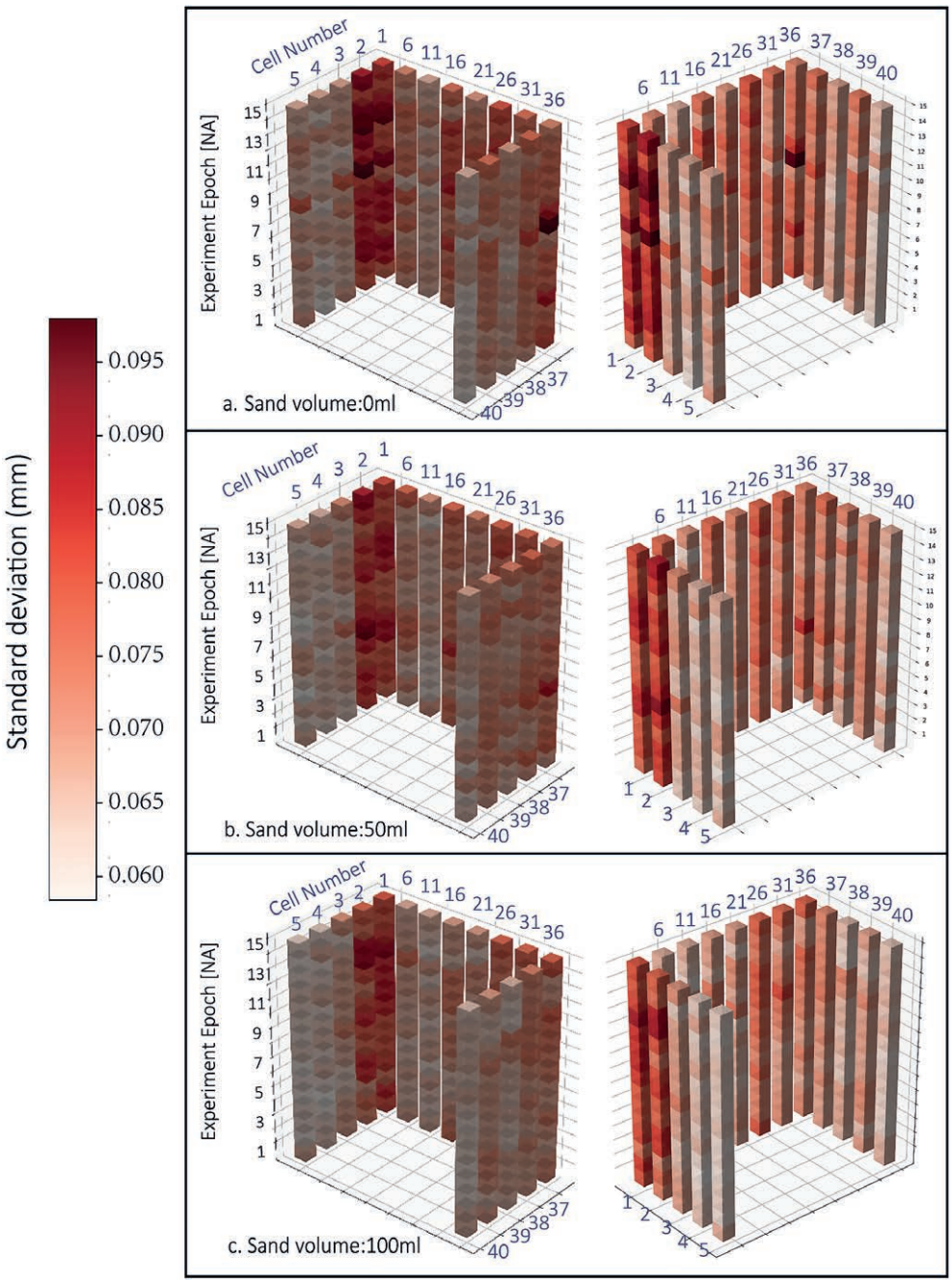


Fig. 5 Spatial Variability of the altitude (Z) standard deviation; (a) no extra sand, (b) 50 ml of sand added, and (c) 100 ml of sand added. The cells used for comparison are the one on the periphery of the experimental box, where no topographic change occurred over all the experiments. Each repeat of the experiment is displayed as a vertical level. The views on the left and right for each experiments a, b and c show the data from a different angle for easier reading.

4.4 Comparison with Geomorphological structures

In order to apply the error analysis to the actual terrain, based on the experimental results of this study, the error index is calculated according to formula 2.

$$E_h = \frac{Z_{max} - Z_{min}}{h} \times 100\% \quad (2)$$

Where E_h is the range of elevation fluctuation. Z_{max} and Z_{min} are the maximum and minimum values of the average elevation of the midpoint in the grid cell, respectively. is the average elevation of the grid cell. The calculation results are shown in the Tab. 8, and there is the lowest elevation without adding sand, that is, the thickness of the acrylic sheet, which is about 10.723 mm. The variability error at this point is about 0.431% to 0.959%. After adding 50 ml of sand, the elevation reaches about 29.868 mm, and the error decreases, ranging from 0.312 to 0.763%. After adding 100 ml of sand, the elevation is 37.535 mm, and the error range becomes larger at this time, rising to 0.256~1.226%.

Tab. 8 Relationship between height and error range.

Sand volume (ml)	Height of sand table (mm)	Error range
0	≈ 10.723	0.431~0.959%
50	≈ 29.868	0.312~0.763%
100	≈ 37.535	0.256~1.226%

For flat cells that do not undergo topographic changes throughout, their variability will also be affected by changes in the central topography. In the absence of additional sand, the variability in these areas ranges from 0.0058 to 0.1047 mm, with a mean of 0.075 (e.g. Fig. 6). When the microtopography of the central area fluctuates, the variability decreases significantly, ranging from 0.0421 to 0.0719, and the variability becomes relatively evenly distributed, concentrated around the average value of 0.0609 (e.g. Fig. 6). Considering the micro-topography with a 100 ml of sand, the measured vertical variability increaed, with variability ranging from 0.0608 and 0.1333. The change range was far greater than the previous two cases (e.g. Fig. 6). This suggests that even in areas where no terrain change has occurred, the error will be affected by the surrounding terrain. However, the error range measured in the present set of experiments is inferior to the grain-size height (0.5 mm) by almost a factor of 5, even for the highest recorded values. As the authors have used a rigid acrylic sheet, which can be taken as perfectly flat, the total error of the model can be represented as a combination of the measured precision (0.1333 mm) and the variability induced by the particles over the acrylic sheet (with values between 0 and 0.5 mm, or half the particle height if one only considers the upper half of the particles).

4.5 Comparison with error arising from topographic change

Common sources of error linked to topographic change when using SfM-MVS are linked to at least four important sources: (1) perspective distortion: Steep topography can cause perspective distortion in the captured images. This distortion affects the accuracy of the feature matching and triangulation processes in SfM. The perspective projection equation, which relates 3D world coordinates to 2D image coordinates, is sensitive to large depth variations (Hartley and Zisserman 2004); (2) depth uncertainty: In areas of steep topographic changes, the depth estimation from triangulation becomes less reliable, because the depth uncertainty is inversely proportional to the baseline (distance between camera positions) and directly proportional to the depth (Gallup et al. 2007). Steep surfaces often have larger depths relative to the baseline, leading to higher depth uncertainty; from 1 and 2, then (3) occlusions and visibility will increase the error (e.g. Furukawa and Ponce 2010). Finally, (4), steep topographic changes can make it challenging

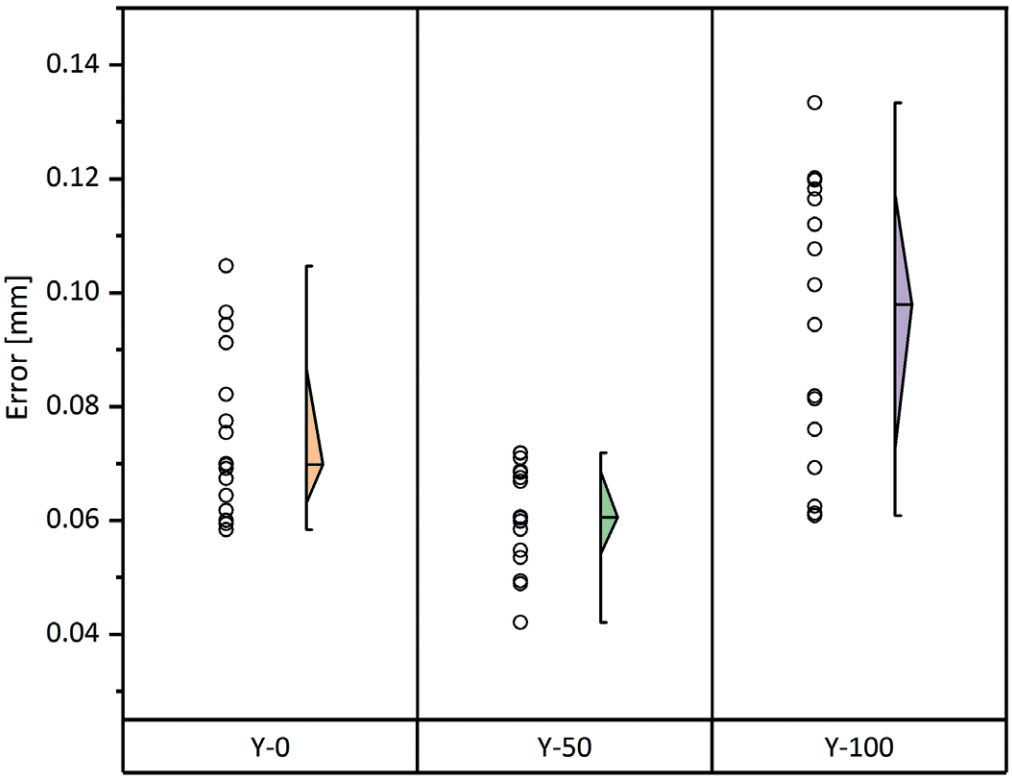


Fig. 6 Changes in flat cell variability. The error range < sand grain-size, potentially suggesting that maximum grain-size on an outdoor surface may be a good indicator of precision variability under similar conditions.

to accurately estimate surface normals, as the local neighborhood around a point may have significant depth variations (Kazhdan and Hoppe 2013). In the present case however, the topographic change are all resulting from a regular dome-shaped controlled by the sand internal-friction angle, and the source of variability is thus different, however the increased error at the corners (Fig. 5) may be related to a difficulty to estimate the normal, due to the immediate location at the edge of the acrylic sheet, but it remains insufficient in explaining the variability between the different types of experiments.

The present contribution confirms the recognized diffusion of error across a measured scene, but it newly demonstrates that the "tele-connection" of errors are driven by the topographic variability, and that repeated measurements need to be considered in order to address inherent error due to measurements. It also demonstrates that the relation between topographic height and variability in the recorded values is not linear, and according to the existing literature on steep slopes and SfM-MVS error, the error is likely to increase with the slope of the topographic feature. Interestingly, the experiments were all conducted with the same lighting and homogeneous single color sand surface, but yet spatial variability in the error was also apparent showing the need to mitigate both precision problems linked to the method and the target (as three sets of vertical variability were tested). This is particularly important when attempting to measure erosion and other surface changes over time, and the variability observed in the present set of experiments may be exacerbated or multiplied under the influence of other factors.

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Analysis of rainfall epochs in changing climate of Kangsabati river basin, India

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ABSTRACT
Climate change directly or indirectly impacts the global atmosphere composition, which poses major environmental concern. The implications of climate change show noticeable change in rainfall patterns and onset worldwide. Prior knowledge of information of rainfall data is vital for many applications. In the present study, the onset, withdrawal, and duration of monsoon period have been studied for Purulia and Ranibandh locations in the Kangsabati river basin area for the period 2015 to 2022. The observed data were analysed and compared with the model data of CMIP6 GCM's for 4 scenarios. Statistical parameters such as probability density function (PDF), Cumulative Distribution Function (CDF), Coefficient of determination (R^2), and Root Mean Square Error (RMSE) were employed to evaluate the precision of matching between observed and modelled rainfall data. For onset, withdrawal, and duration of monsoon period, under 4 scenarios of Shared Socioeconomic Pathways (SSPs), highest R^2 values range between 0.46 and 0.75 for CanESM5, EC-Earth3-veg and ACCESS-CM2 for Purulia and Ranibandh locations. For the duration of monsoon period between onset and withdrawal, R^2 value of 0.54 and 0.46 has been observed for CanESM5-SSP370 and ACCESS_CM2-SSP126 for Purulia and Ranibandh respectively. On the other hand, for Purulia and Ranibandh, the lowest RMSE values has been observed for the model CanESM5, EC-Earth3-veg and ACCESS-CM2 for onset, withdrawal and monsoon period. The study identifies CanESM5, EC-Earth3-veg, and ACCESS-CM2 as the top-performing CMIP6 GCM models for accurately simulating monsoon dynamics onset, withdrawal, and monsoon length – in the Kangsabati basin, specifically in Purulia and Ranibandh locations. With these best performing models on projecting the precipitation for 2023 to 2100 for Purulia and 2022 to 2100 for Ranibandh, a very negligible shift has been observed in the onset and withdrawal periods. Overall, this study contributes to our understanding of rainfall patterns and monsoon dynamics, offering valuable insights for both climate modelling and water resource management in the region.

KEYWORDS
climate change; precipitation projection; rainfall patterns; water resource management

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1. Introduction

The climate of a region encompasses the long-term average weather patterns, while climate change refers to statistical alterations in the average state of the climate and its key components over a significant duration. As defined in Article 1 of the United Nations Framework Convention on Climate Change, climate change is a shift attributed to human activity, directly or indirectly impacting the global atmosphere's composition, surpassing natural variability. Undoubtedly, climate change stands out as a major environmental concern in the twenty-first century, causing apprehension in economic, societal, and international scientific and political spheres. Its repercussions, particularly the rise in extreme weather events, significantly affect agriculture, ecosystems, and water resources (Arnell and Reynard 1996; Kumar et al. 2020), posing substantial challenges to global industrial systems and supply chains (Papadopoulos and Balta 2022).

According to the Intergovernmental Panel on Climate Change (IPCC 2023), earth's surface temperature was around 1.1 °C above the period 1850–1900 in 2011–2020, with larger increases over land than over the ocean. Climate fluctuations and changes impact virtually every individual globally, with South and Southeast Asian nations facing disproportionate effects due to poverty and complex socio-economic issues (Omerkhil et al. 2020). India, with its developing economy and diverse geographic regions, is particularly sensitive to climate hazards. Over half of India's population resides in rural areas, heavily dependent on climate-sensitive sectors like agriculture, fisheries, and forestry. Rural communities, constituting 70% of the population, are particularly vulnerable (Parry et al. 2007).

A notable consequence of the Earth's surface temperature increase is the atmosphere's increased water-holding capacity by approximately 7% per 1 °C rise, directly leading to intensified rainfall (Tabari 2020). Recent research highlights an increase in extreme rainfall occurrences and their intensity within a warming climate (Roxy et al. 2017). The non-stationary approach, considering changing climates and escalating urbanization, is deemed more appropriate for evaluating extreme rainfall (Vinnarasi and Dhanya 2022).

Historical climate model simulations, primarily assessing models' capabilities in replicating average and extreme precipitation, are crucial for climate projections. The Coupled Model Intercomparison Project (CMIP) has evolved through various phases, with CMIP6 being the latest. CMIP6 introduces advancements in spatial resolution, physical parameterizations, and the inclusion of additional Earth system processes compared to its predecessors (Eyring et al. 2016; Chen et al. 2020). Despite discrepancies, CMIP6 demonstrates improved precipitation simulation abilities (Abbas et al. 2022; Abbas et al. 2023; Towheed and Roshni 2021). However, a thorough investigation is required to assess CMIP6 models' enhancements in simulating precipitation across different scales.

Researchers and policymakers are interested in evaluating the accuracy of CMIP6 Global Climate Models (GCMs) in representing global and regional climate patterns and predicting changes in extreme precipitation under new emissions scenarios. However, despite the improvements and efficacy of current CMIP6 models in conjunction with SSPs, there is still very limited studies on anticipated rainfall extremes, particularly for Kangsabati river basin. Additionally, studies focusing on GCMs for climate change research in Kangsabati river basin was found scarce. Therefore, this study emphasizes the need for reliable assessments of extreme rainfall for designing infrastructure and flood protection, determining rainfall frequency, comparing predictive approaches, and estimating risks associated with extreme damage. Hence, the objectives of this study are to (i) Evaluate the comparative performance of observed data with different climate change models CMIP6 model data for 4 SSP scenarios at Purulia – the Ranibandh gauging stations, using different Goodness_of_fit statistics, for Onset, Withdrawal, Length of monsoon rainy days (ii) To determine the projected precipitation changes for the Onset, Withdrawal and Length of monsoon rainy days, for the period 2023 to 2100 for Purulia and 2022 to 2100 for Ranibandh, based on the best performing CMIP6 GCMs for 4 scenarios. Given the prevalence of natural disasters in this region and the critical shortage of water for agricultural, industrial, and domestic purposes, this study is essential for identifying extreme hydro-meteorological factors in climate change scenarios. This understanding will facilitate effective water management for sustainable agriculture and help mitigate natural disasters such as floods and droughts (Kumar and Singh 2024). The study's outcomes aim to provide valuable insights for water resource policymakers and decision-makers to make informed decisions in the face of climate change challenges.

2. Study Area and Data Collection

The Kangsabati River Basin is a sub-basin of the lower Ganga plain in West Bengal. The Kangsabati River is a non-perennial alluvial river which originates from the eastern part of the Chotta Nagpur plateau i.e. at the Jhalda block of Purulia district. It then flows through the districts of Purulia, Bankura, West and East Midnapore and meets River Rupnarayan before it falls into the Bay of Bengal. The upper course of the river flows in the Purulia district, middle course flows through Bankura and West Midnapur while the lower course of the river is in East Midnapur where the river meets River Rupnarayan.

The study area of the Kangsabati River basin extends from 23°28′15.6″ N 85°57′3.6″ E and

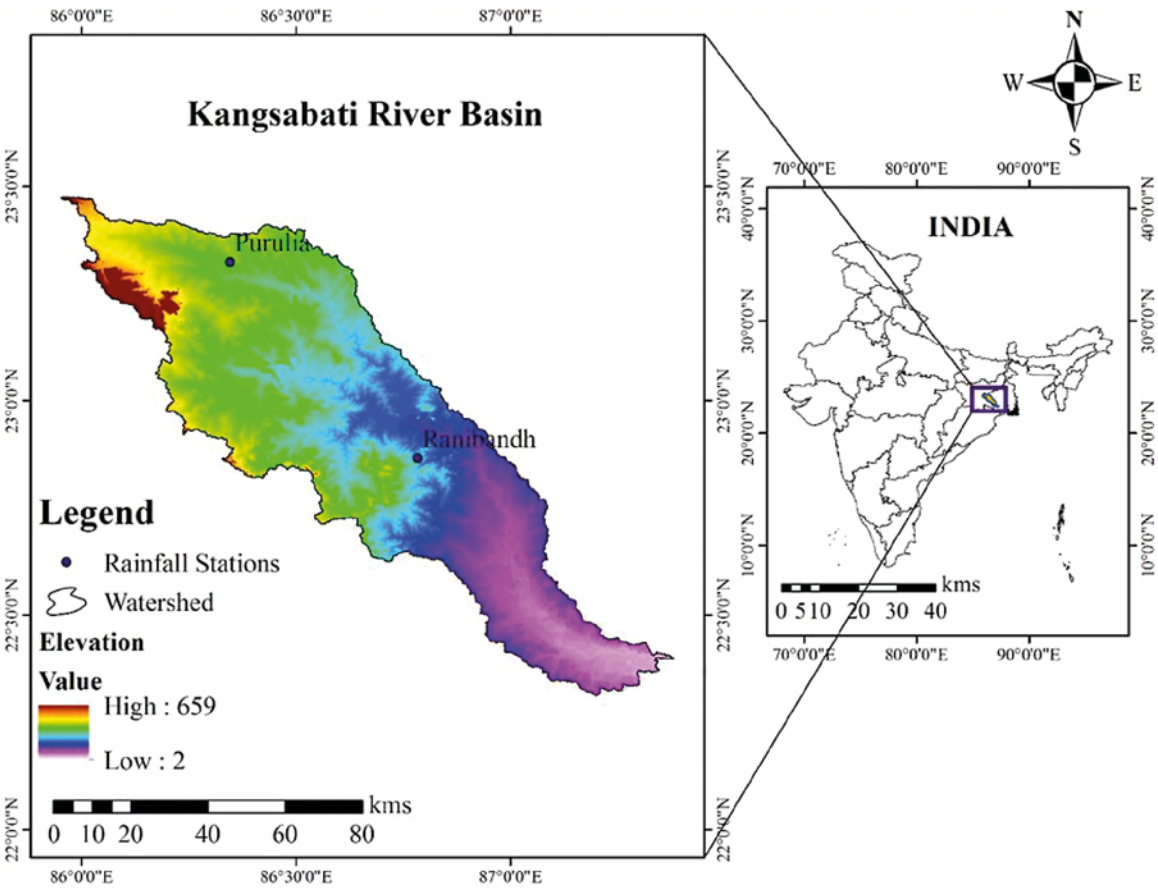

Fig. 1 Catchment area of the Kangsabati River Basin.

22°23′56″ N 87°22′40.8″ E, with a total area of 9658 km^2 is shown in Fig. 1. In 1956, Mukutmanipur Dam or Kangsabati dam, was constructed at the border of Purulia and Bankura districts near Mukutmanipur, creating a large reservoir, also known as the Kangsabati Irrigation Project/Kangsabati Reservoir Project, developed to provide water for the irrigation of Bankura and Midnapore districts. The temperature varies from 27 °C to 45 °C during summer, 6 °C to 25 °C during winter and the annual rainfall varies from 960 mm to 1822 mm with an average of 1370 mm (Central Ground Water Board 2014–15). However, 80–85 percent of the total rainfall is received during the three to four months of the monsoon period from June to September. The land is undulated and lateritic.

2.1 Datasets

The observational data utilized in this research consists of daily rainfall records obtained from IMD, Pune, covering the period of 1982 to 2022 for Purulia and 1990 to 2021 for Ranibandh. We scrutinized three CMIP6 models from the CMIP6 database website (https://esgf-node.llnl.gov/search/cmip6), as detailed in Tab. 1. Unlike CMIP5, the latest generation of CMIP6 models features updated specifications for concentration, emission, and land-use scenarios, along with a revised start year (CMIP6: 2015, CMIP5: 2006) for future scenarios. In this phase, Shared Socioeconomic Pathways (SSPs) are amalgamated with the Representative Concentration Pathways (RCPs) of CMIP5. These SSPs are based on five narratives representing different levels of socioeconomic development (Riahi et al. 2017): sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil fuel-driven development (SSP5). Detailed descriptions of the SSPs are available in O'Neill et al. (2016).

Tab. 1 List of CMIP6 models used in this study.

GCM	Research Center	Resolution
ACCESS-CM2	Australian Community Climate and Earth System Simulator – Climate Modelling2	1.88 × 1.25
CanESM5	Canadian Earth System Model version 5, CanESM5, Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Canada	2.81 × 2.77
EC-Earth3-veg	One of the EC – Model Earth configurations for CMIP6, Royal Netherlands Meteorological Institute	.7 × .7

2.2 Methods/Model Performance Criteria

Rainy days are defined as days when the rainfall exceeds the threshold of 2.5 mm or 0.1 inches (Epifani et al. 2004; Tilya and Mhita 2007). Onset is the first day when rainfall exceeds the defined threshold after a consecutive dry period, identified as the onset date. Withdrawal is defined as the last day when rainfall exceeds the threshold of 2.5 mm before a dry period. The duration of each monsoon period was calculated by subtracting the onset date from the withdrawal date. Statistical analysis was conducted to determine the relationship between the model and observed data.

The assessment of CMIP6 models' ability to replicate extreme rainfall, in comparison to observed data, involved employing Root Mean Square Error (RMSE) and Coefficient of determination (R^2) metrics (Ongoma et al. 2018; Dibaba et al. 2019). An R^2 close to 1 indicates a good correlation while values approaching zero indicated poor model performance with a weak correlation (Chai and Draxler 2014; Demissie and Sime 2021; Sime and Demissie 2022). While R^2 tells you about correlation between two datasets,

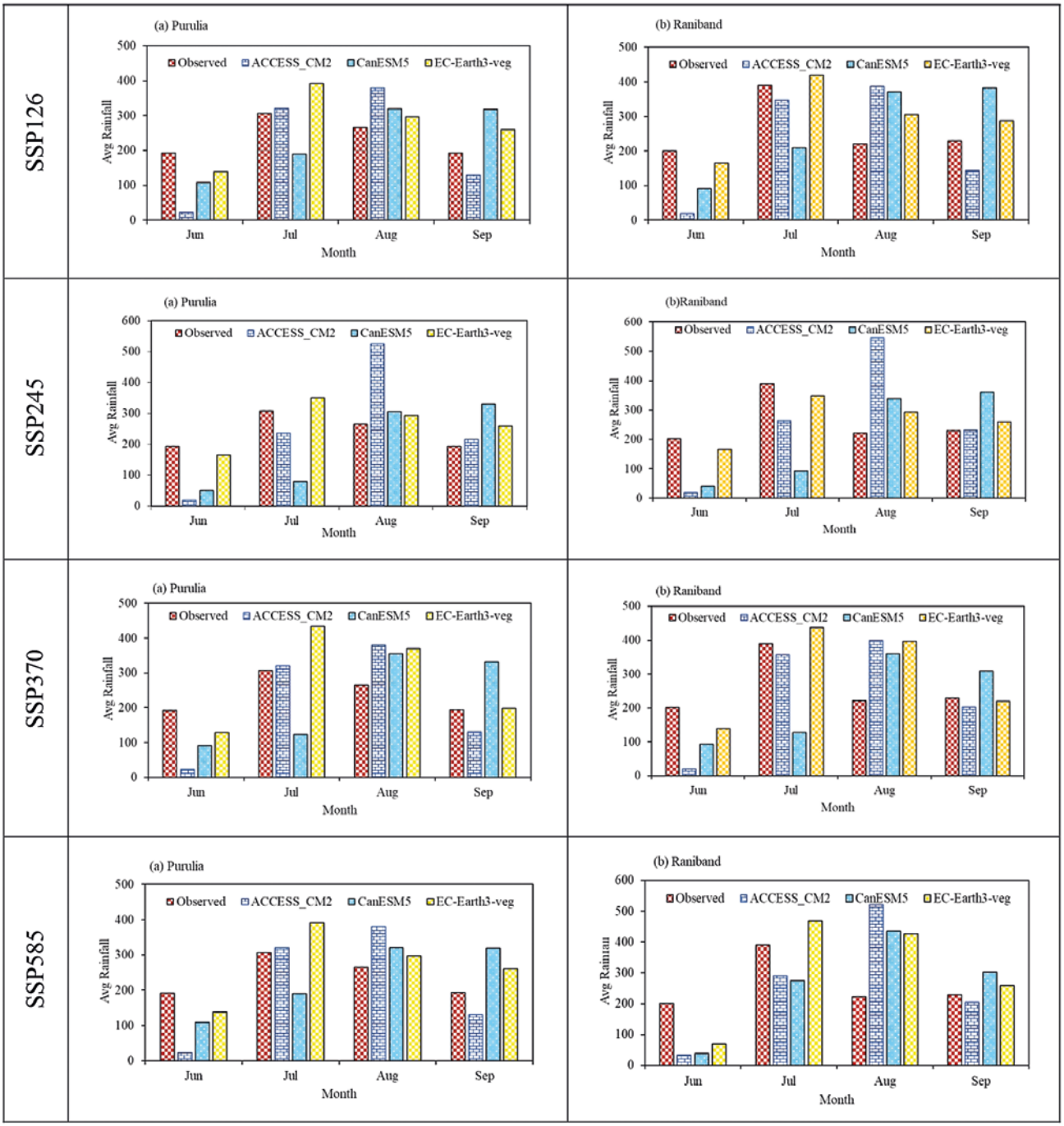

Fig. 2 Monthly Average rainfall data comparison between Observed IMD data set and 3 climatic model data sets for 4 scenarios from 2015 to 2022 for both Purulia and Ranibandh locations.

RMSE tells you about the difference between them. A low RMSE means less difference between model data and observed measurements and hence better performance and vice versa. Ideal Value of R^2 is 1 and ideal value of RMSE is 0.

The specific equations for calculating R^2 and RMSE are outlined in equations (1) and (2), respectively.

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - O_m)(S_i - S_m)}{\sqrt{\sum_{i=1}^{n}(O_i - O_m)^2}\sqrt{\sum_{i=1}^{n}(S_i - S_m)^2}}\right]^2 \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \quad (2)$$

Where S_i is simulated or model data and O_i is the observed value of the climate variable, i refers to the simulated and observed pairs, n is the total number of pairs, and m refers to mean extreme rainfall.

3. Results and Discussion

3.1 Comparison with Global dataset

Spatio-temporal trends in rainfall is assessed using historical rainfall datasets. Analysis of rainfall is important for many reasons. It can help to understand the effects of climate change and variability on water resources, ecosystems, floods, and droughts. It

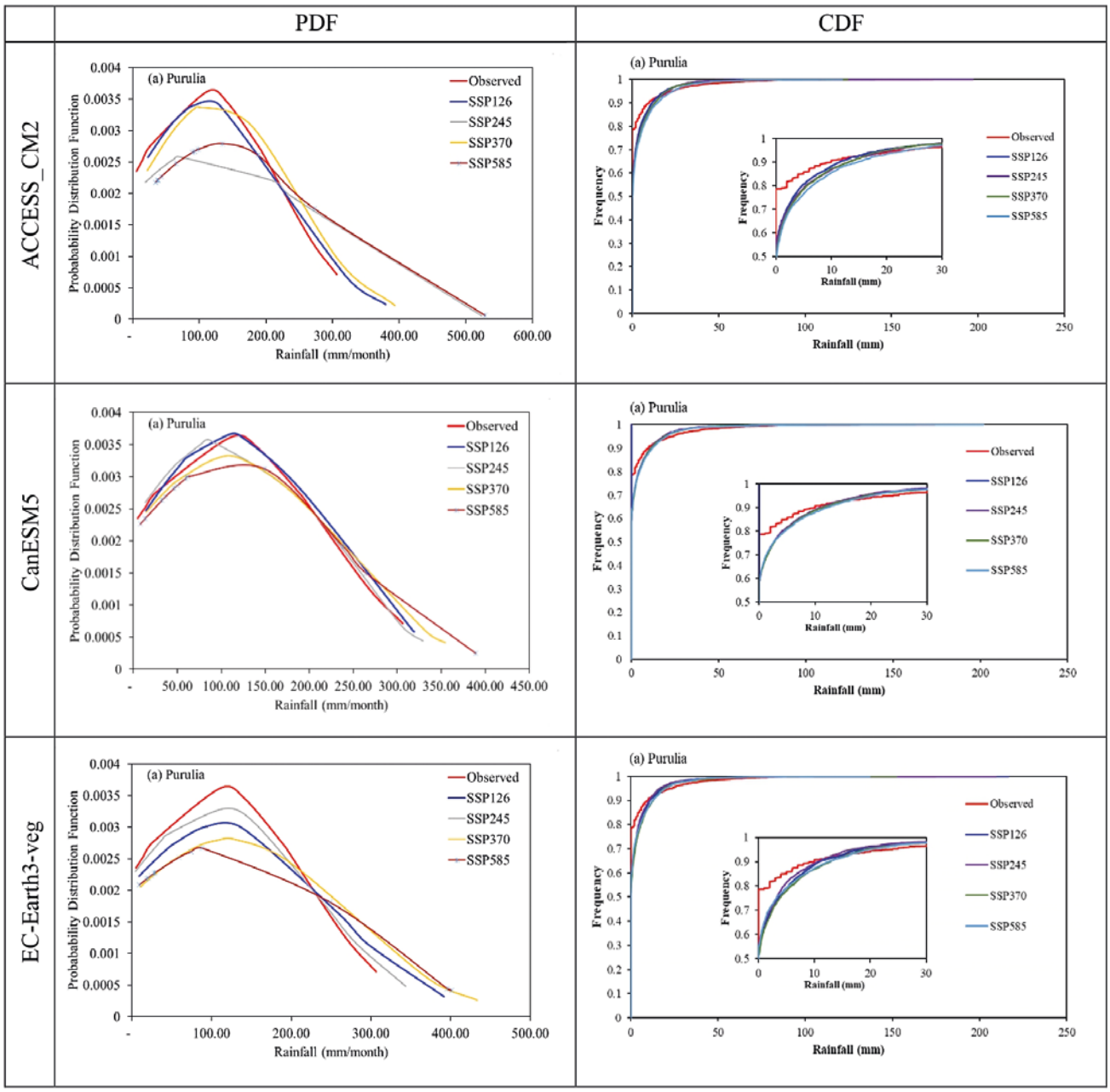

Fig. 3a Comparison of PDF and CDF plots of monthly variation of Observed data and 3 models for Purulia during the period 2015–2022.

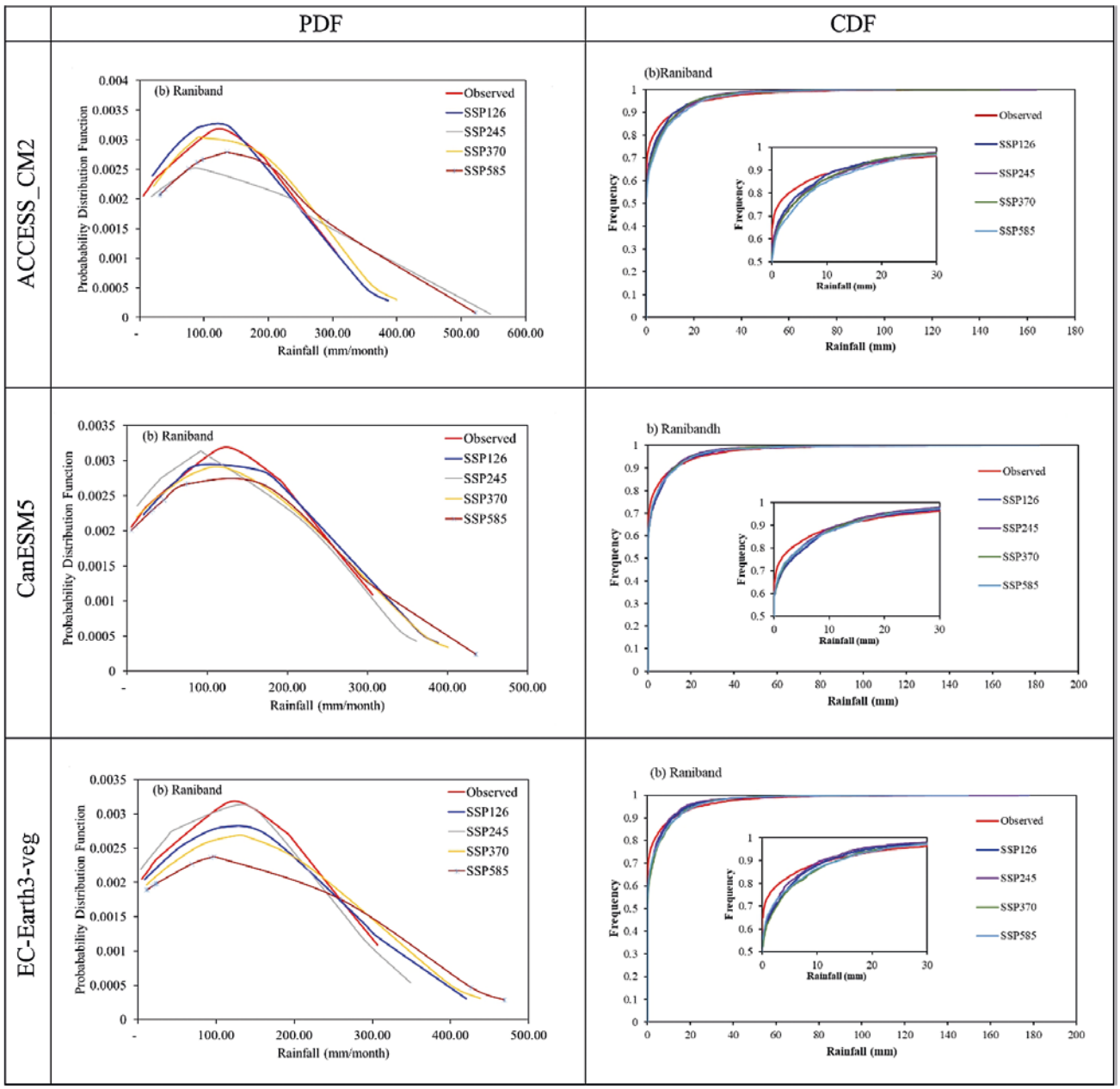

Fig. 3b Comparison of PDF and CDF plots of monthly variation of observed data and 3 models for Ranibandh during the period 2015–2021.

can provide information on the spatial and temporal variability of precipitation, as well as its trends and anomalies. It can support hydrological modelling and forecasting, climate monitoring and analysis, agricultural and water resource management, and disaster risk reduction and humanitarian response.

Here the spatio-temporal changes in rainfall of observed data and model data with four scenarios of each model has been analysed using the monthly average data of monsoon season i.e. June to September from 2015 to 2022 for Purulia and Ranibandh. Three GCM models ACCESS-CM2, CanESM5 and EC-Earth3-veg having four land scenarios namely SSP126, SSP245, SSP370 and SSP585 have been used in the study.

From the analysis of Fig. 2, it is found that among the datasets of three models, EC-Earth3-veg matches more with the observed data of both Purulia and Ranibandh. This alignment implies that EC-Earth3-veg would be better able to represent the regional rainfall variability and local climatic dynamics. Because the model accurately simulates monsoonal precipitation, it may be able to reproduce actual rainfall patterns due to its detailed depiction of atmospheric processes and land-atmosphere interactions.

3.2 Comparison of PDF and CDF

The probability density function (PDF) and cumulative distribution function (CDF) of rainfall for each

year at two stations are plotted and shown in Fig. 3. A comparison of the probabilities shows good agreement between the IMD and model data. PDF plots were generated to compare the observed data with climate rainfall data for two stations over the period from 2015 to 2022 for Purulia and 2015 to 2021 for Ranibandh. These plots provide insights into the mean and variance of the chosen data and allow for a visual comparison between the observed and climate-derived rainfall (Fig. 3a and 3b). The PDF plots were constructed by plotting the range of rainfall intensity on the x-axis, measured in millimetres per month, and the corresponding frequency of events falling within each range of rainfall intensity on the y-axis.

Figures 3a and 3b shows that the models ACCESS-CM2 and EC-Earth3-veg, under scenarios SSP126 and SSP370 for both Purulia and Ranibandh, are very close to the observed datasets, indicating that most of the rainfall datasets lie in the range of 100 to 200 mm/month. The observed agreement between the modelled and actual data indicates that the chosen climate models are capable of accurately simulating the features of regional rainfall. Understanding long-term climate trends and evaluating the possible effects of climate change on precipitation patterns in Purulia and Ranibandh depend on this agreement. Furthermore, these models well reflect the central tendency and variability of rainfall distribution, as evidenced by the similarity in mean and variance between the observed and modelled datasets. All things considered, the PDF analysis clearly validates climate models' ability to replicate past rainfall patterns for these two locations. These models may be used to confidently predict future rainfall variability under various climate change scenarios, as evidenced by the high degree of agreement between observed and modelled data. The CanESM5 model also shows a significant correlation with the observed datasets under all examined scenarios. The accuracy of this model in replicating the regional rainfall distribution is further supported by the CanESM5 simulations' preponderance of rainfall falling between 100 and 200 mm/month. The reliability of these estimates is demonstrated by the consistency of trend across several climate models and scenarios.

The CDF analysis further highlights the differences in maximum daily rainfall values between observed

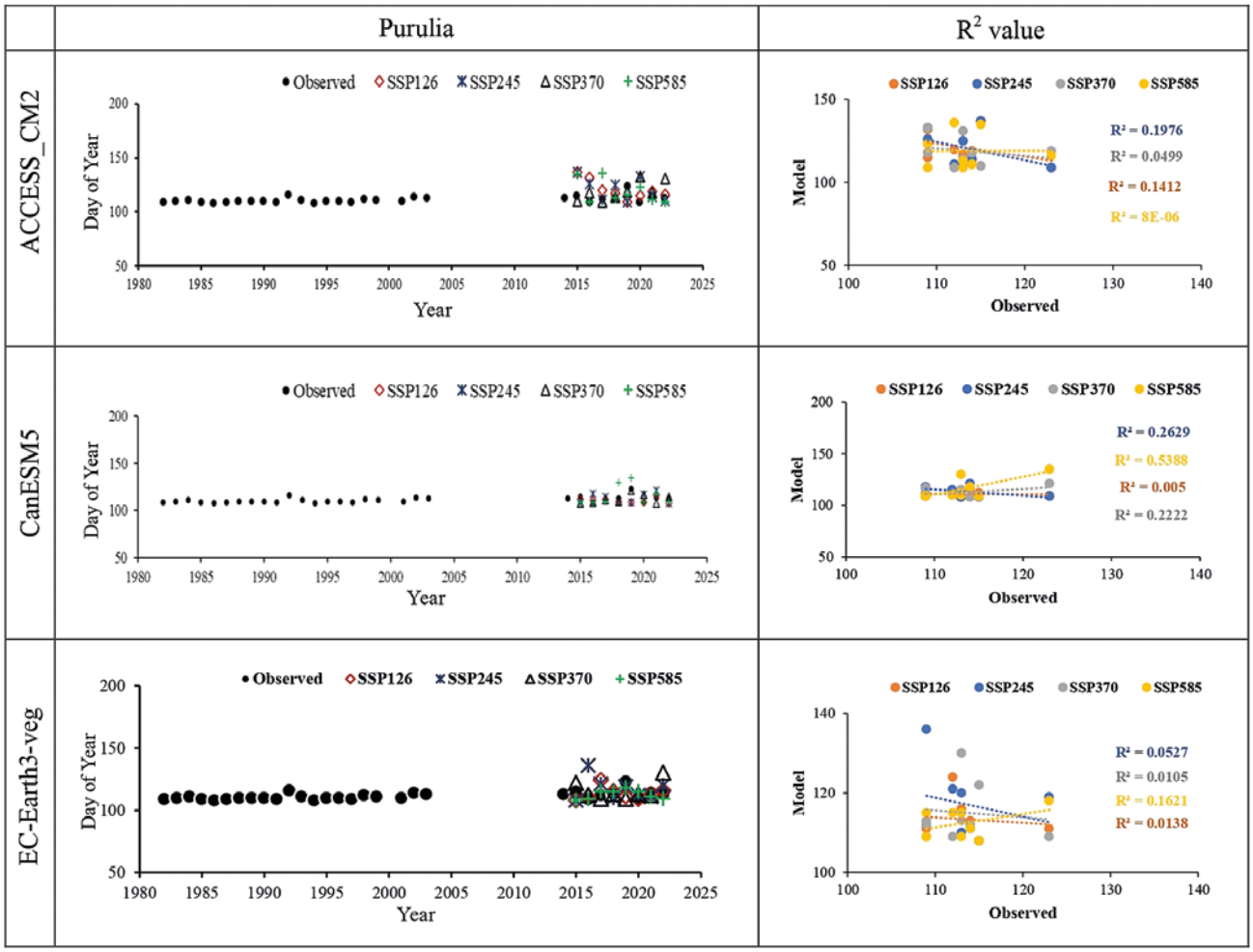

Fig. 4a Monsoon season onset plot of observed and model data for Purulia and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2022.

and modelled datasets. It represents the probability that the precipitation value falls below a certain threshold. The CDFs of observed daily rainfall and the raw datasets from three climate models are plotted for Purulia, as shown in Figure 3a and 3b. The magnitudes of the CDFs from ACCESS-CM2, CanESM5, and EC-Earth3-veg are much higher than the observed CDF, especially for the maximum cumulative distribution. This is because the three climate models produce higher maximum daily rainfall, as shown earlier. Thus, EC-Earth3-veg exhibits a larger maximum CDF rainfall value (Max rain = 216.71 mm), CanESM5 (Max rain = 201.82 mm) surpasses ACCESS-CM2 (Max rain = 197.06 mm), and the observed data (Max rain = 175 mm) for Purulia and CanESM5 exhibits a larger maximum CDF rainfall value (Max rain = 181.75 mm), EC-Earth3-veg (Max rain = 177.98 mm) surpasses ACCESS-CM2 (Max rain = 163.93 mm), and the observed data (Max rain = 129.30 mm) for Ranibandh. This discrepancy indicates that extreme rainfall events are often overestimated by climate models, which should be taken into account in upcoming assessments of the effects of climate change and adaptation plans.

3.3 Onset of Monsoon

Generally, there is no coherent spatial pattern to monsoon onset or withdrawal based on precipitation, a finding consistent with other monsoon regions (Marteau et al., 2009). While the absence of any spatially coherent monsoon advancement or retreat may seem unusual, it's worth noting that our study domain is much smaller than that of many monsoon studies.

The onset day for each year of the observed data i.e. from 1982 to 2022 and 1990 to 2021 has been plotted along with a comparison made between the observed and the 3 climatic model data for 4 scenarios in Purulia and Ranibandh respectively. The graphic representation of this data along with the R^2 value obtained for each scenario of the 3 models for Purulia and Ranibandh locations are shown in Fig. 4a and Fig. 4b.

The R^2 values were calculated for onset of monsoon data for Purlia and Ranibandh stations and is shown in Tab. 2 (rounded off to two decimals). In Purulia, under the SSP585 scenario of CanESM5 model, a notably higher R^2 value of 0.54 is observed, surpassing all other datasets of ACCESS_CM2 and EC_Earth3-veg

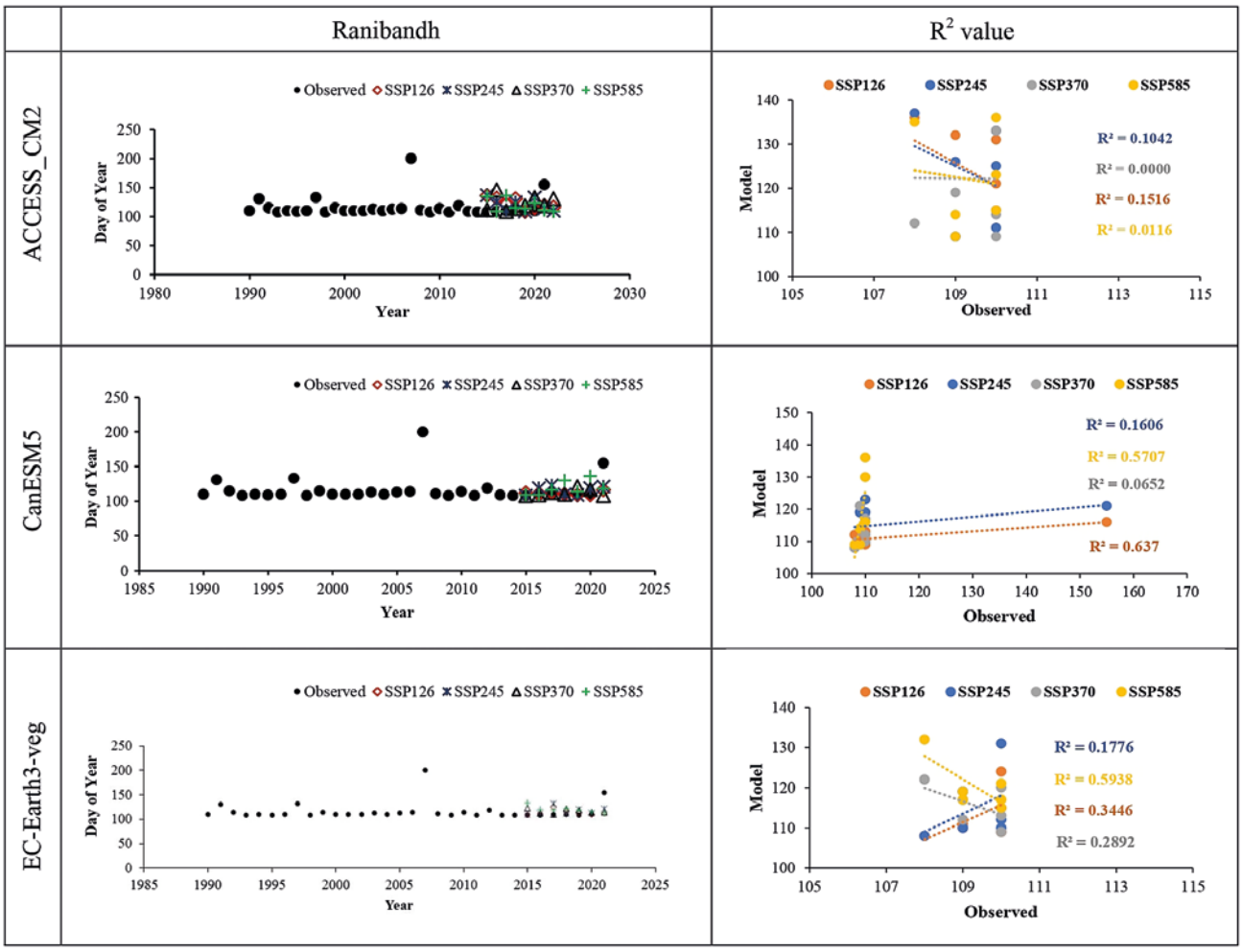

Fig. 4b Monsoon season onset plot of observed and model data for Ranibandh and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2021.

Tab. 2 The R^2 values for Purulia and Ranibandh for Onset of Monsoon data.

		SSP126	SSP245	SSP370	SSP585
Purulia	ACCESS_CM2	0.1400	0.20	0.05	0.000008
	CanESM5	0.0050	0.26	0.22	**0.540000**
	EC_Earth3-veg	0.0100	0.05	0.01	0.160000
Ranibandh	ACCESS_CM2	0.1500	0.10	0.00	0.010000
	CanESM5	**0.6400**	0.16	0.07	0.570000
	EC_Earth3-veg	0.3500	0.18	0.29	0.590000

Tab. 3 The R^2 values for Purulia and Ranibandh for Withdrawal of Monsoon data.

		SSP126	SSP245	SSP370	SSP585
Purulia	ACCESS_CM2	0.0400	0.09	0.24	0.0042
	CanESM5	0.0600	0.24	0.14	0.1400
	EC_Earth3-veg	0.2900	0.08	0.05	**0.7500**
Ranibandh	ACCESS_CM2	0.2900	0.11	0.16	0.5100
	CanESM5	0.0002	0.24	0.05	0.3700
	EC_Earth3-veg	**0.5600**	0.27	0.09	0.1200

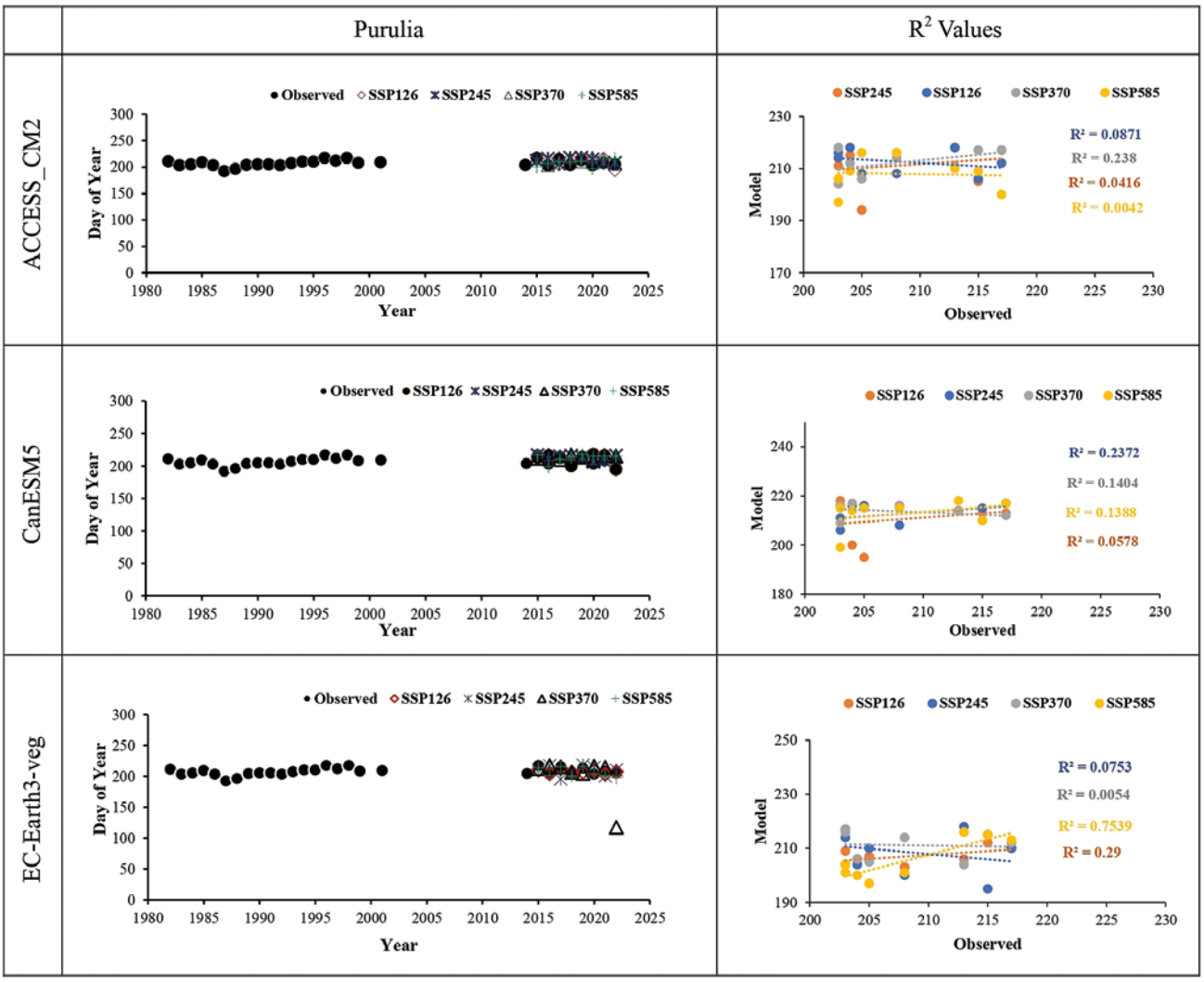

Fig. 5a Monsoon season withdrawal plot of observed and model data for Purulia and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2022.

model. This higher value indicates a strong and positive relationship between the observed onset days and model data in the Purulia region. The superior performance of CanESM5 over the other models may be attributed to its advanced representation of climate processes and interactions, which could be particularly relevant in the context of the socio-economic and environmental conditions prevalent in Purulia. Similarly, in the Ranibandh region, the R^2 value reaches 0.64 under SSP126 scenario for CanESM5 model, surpassing all other models.

This elevated value indicates a robust and significant relationship between the model and observed data in the Ranibandh region. Overall, these findings underscore the varying degrees of relationship strength observed across different climate models in the specified scenarios, with moderate to strong associations between the observed and modelled data of CanESM5 in Purulia and Ranibandh for SSP585 and SSP126 respectively.

3.4 Withdrawal of Monsoon

Similar to the onset day, withdrawal day for each year of the observed data i.e. from 1982 to 2022 and 1990 to 2021 has also been plotted along with a comparison made between the observed and the 3-model data for 4 scenarios in Purulia and Ranibandh respectively. The graphic representation of this data along with the R^2 value obtained for each scenario of the 3 models is shown in Fig. 5a and Fig. 5b.

The R^2 values were calculated for withdrawal of monsoon data for Purlia and Ranibandh stations and is shown in Tab. 3 (rounded off to two decimals). In the case of withdrawal, in both Purulia and Ranibandh, the data set of EC-Earth3-veg with R^2 value of 0.75 in Purulia under the scenario SSP585 and 0.56 in Ranibandh under the scenario SSP126, surpasses all other model datasets. The R^2 value of 0.74 and 0.56 suggests a strong and positive relationship between the observed and model data in the scenario of

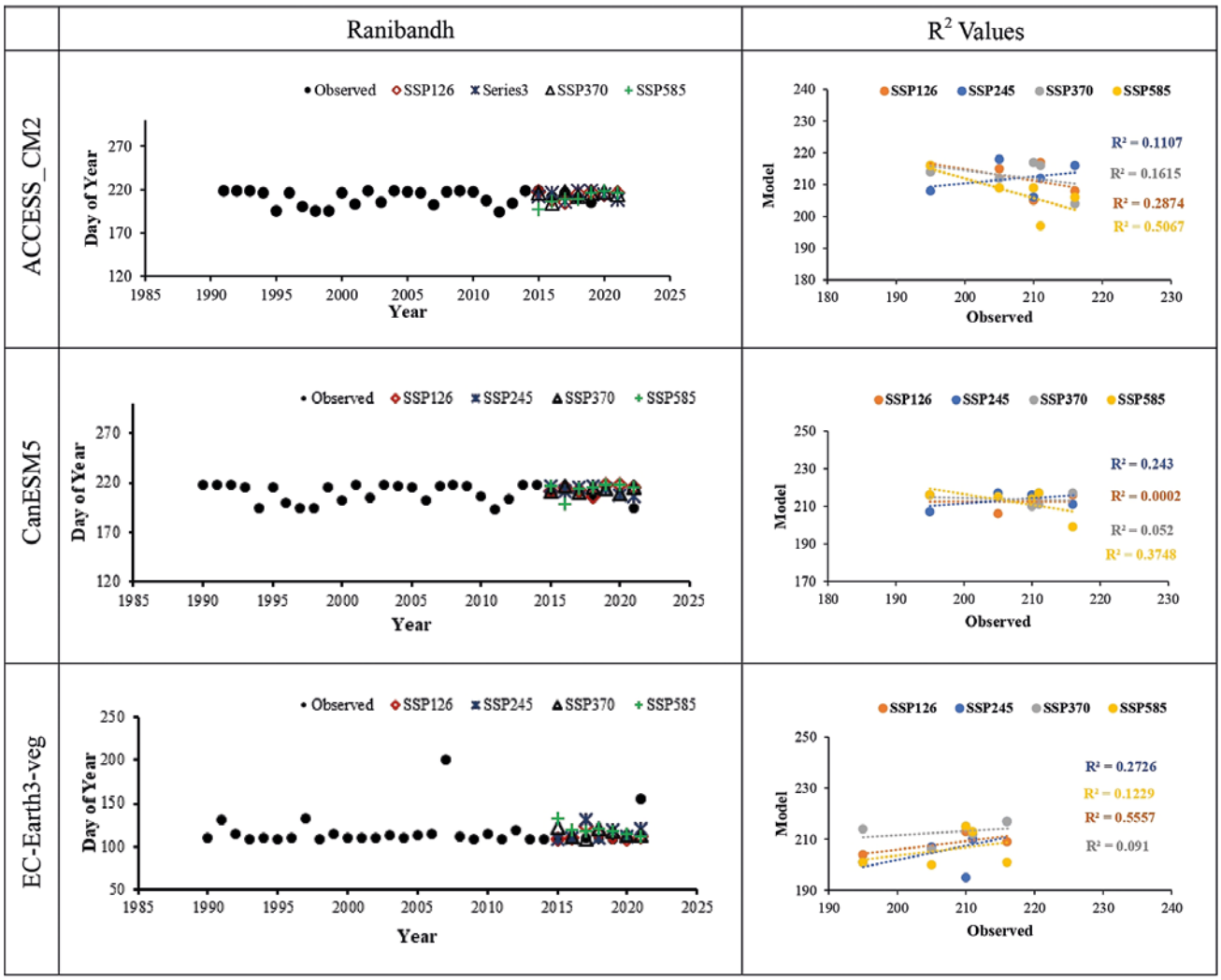

Fig. 5b Monsoon season withdrawal plot of observed and model data for Ranibandh and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2021.

SSP585 and SSP 126 respectively. Overall, these findings underscore the varying degrees of relationship strength observed across different climate models in the specified scenarios, with notable instances of moderate to strong associations between the observed and modelled data.

3.5 Analysis of Monsoon period

The duration of each monsoon period per year is calculated by subtracting the onset date from the withdrawal date. The monsoon period obtained for the observed data is compared with the model data for both Purulia and Ranibandh location points, as per Fig. 6a and Fig. 6b.

In the examination of the duration of rainy days, the Ranibandh station, as simulated by the ACCESS_CM2 model under the SSP126 scenario, yields an R^2 coefficient of 0.46 (Tab. 4), indicating a considerable degree of explanatory power between the observed and modelled datasets. Transitioning to the Purulia region, under the CanESM5 model SSP370 scenario,

Tab. 4 The R^2 values for Length of Rainy Days in Purulia and Ranibandh.

		SSP126	SSP245	SSP370	SSP585
Purulia	ACCESS_CM2	0.002	0.1032	0.1200	0.360
	CanESM5	0.210	0.3300	**0.5400**	0.100
	EC_Earth3-veg	0.170	0.3300	0.0025	0.011
Ranibandh	**ACCESS_CM2**	**0.460**	0.0200	0.1300	0.290
	CanESM5	0.063	0.1930	0.0250	0.042
	EC_Earth3-veg	0.108	0.2500	0.1360	0.002

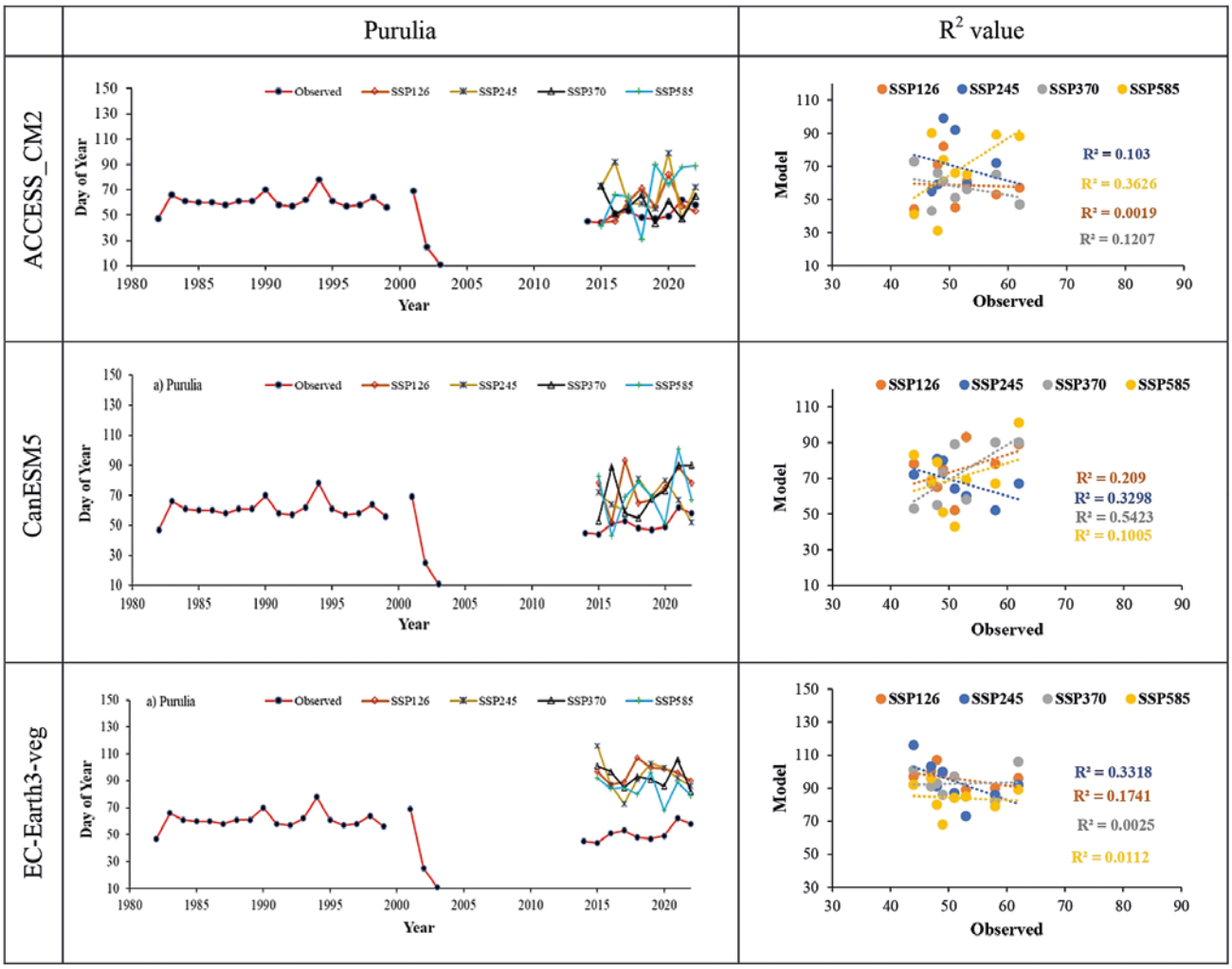

Fig. 6a Monsoon season length plot of observed and model data for Purulia and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2022.

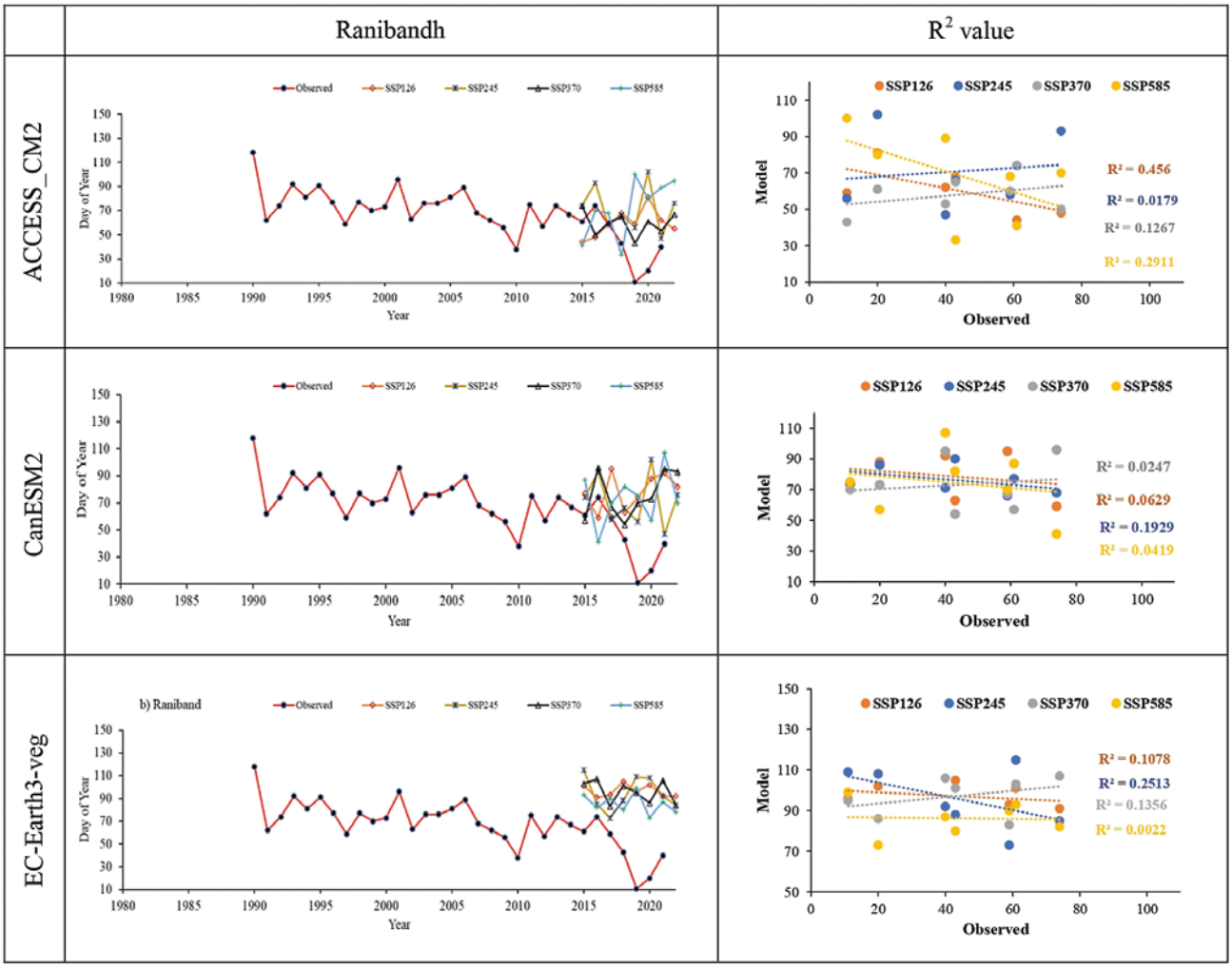

Fig. 6b Monsoon season length plot of observed and model data for Ranibandh and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2021.

a notably elevated R^2 coefficient of 0.54 is discerned, surpassing those within the ACCESS_CM2 model datasets. The high R^2 value denotes very good relationship between the observed and modelled data specifically within the Purulia domain.

3.6 RMSE plot for Monsoon Onset, Withdrawal and Monsoon period

Root Mean Square Error (RMSE) between observed and model data concerning monsoon onset days, monsoon withdrawal days, and the length of rainy days were calculated and is plotted in Fig. 7.

From Tab. 5 for monsoon onset, ACCESS-CM2 model under the scenario SSP245 exhibits highest RMSE value with RMSE value of 14.57 days in Purulia and 22.57 days in Ranibandh. For length of rainy days, the model EC_Earth3_veg in the scenario SSP126 and 245 exhibits highest RMSE value of 45 days and 60 days in Purulia and Ranibandh respectively. While for monsoon withdrawal, EC_Earth3-veg in the scenario SSP585 exhibits highest RMSE value of 10.5 days in Purulia and CanESM5 in the scenario SSP585 exhibits a value of 13.28 days.

Higher RMSE value like this suggests a significant discrepancy between the model predictions and the observed onset of the monsoon. This discrepancy is attributed to its representation of heavier rainfall compared to the Kangsabati river basin, resulting in larger errors across all models.

Conversely, in Purulia and Ranibandh respectively, the model dataset of CanESM5 displays lowest RMSE values i.e. lowest value of 4.5 days and 15 days for monsoon onset, EC-Earth3-veg model gives the lowest RMSE values of 4.3 days and 5.3 days for withdrawal while model ACCESS_CM2 gives reduced RMSE values of 14 days and 24 days, indicating a closer agreement between model predictions and observed rainfall data. Under the SSP585 scenario, the EC-Earth3-veg model and under the scenario SSP370, the CanESM5 model closely approximates observed values, highlighting its effectiveness in simulating monsoon water withdrawal and monsoon length in the Kangsabati basin in Purulia and Ranibandh.

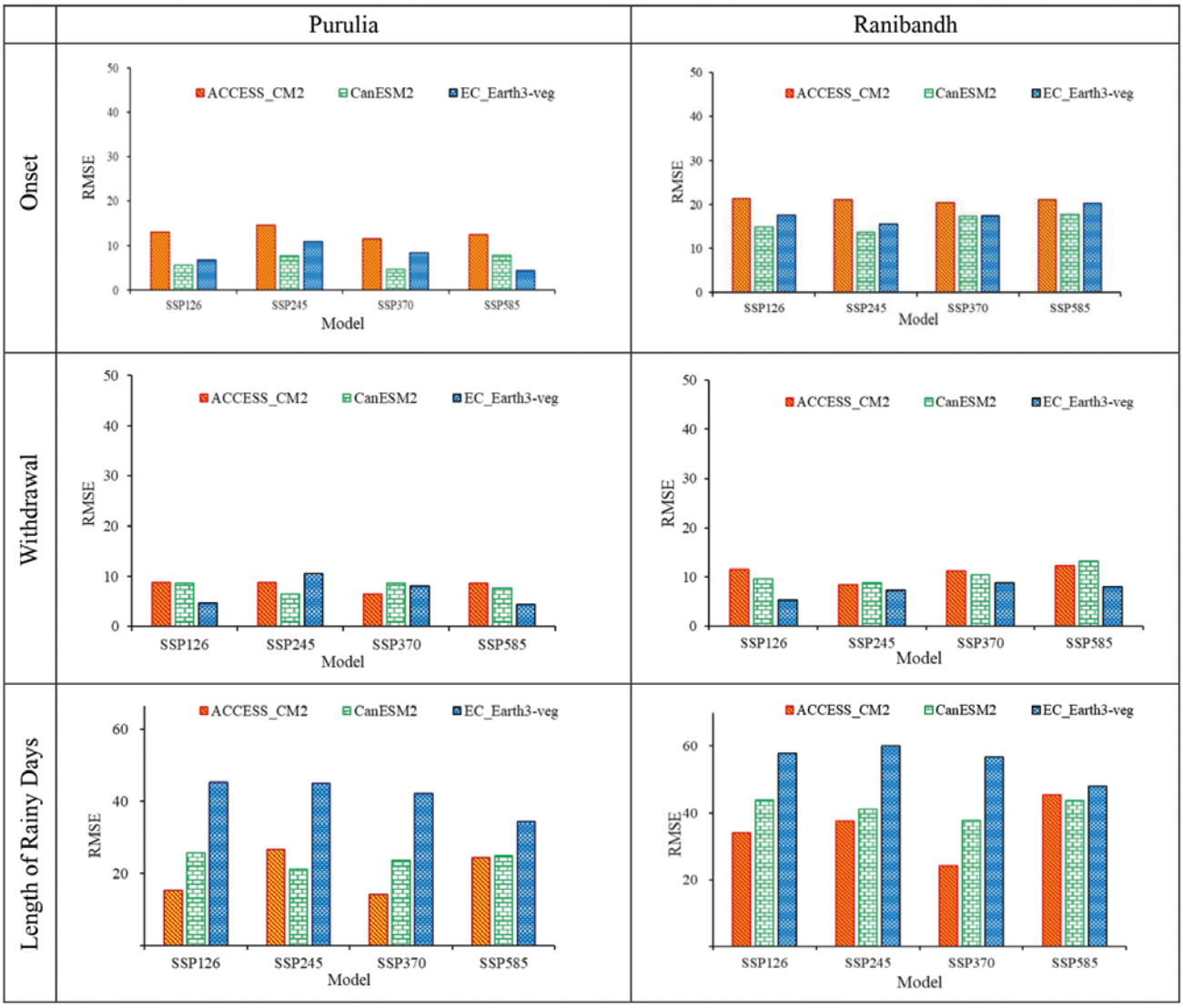

Fig. 7 Bar plot of the RMSE for each climatic model with the Observed rainfall data during the period 2015–2022 for Purulia and 2015–2021 for Ranibandh locations.

Tab. 5 Highest and Lowest RMSE Values for Monsson onset, withdrawal and length of rainydays.

	Purulia		Ranibandh	
	Highest RMSE	Lowest RMSE	Highest RMSE	Lowest RMSE
Onset	ACCESS_CM2, SSP245 (14.57)	CanESM5, SSP370 (4.5)	ACCESS_CM2, SSP245 (22.57)	CanESM5 SSP126 (15)
Withdrawal	EC_Earth3_veg, SSP245 (10.5)	EC_Earth3_veg, SSP585 (4.3)	CanESM5, SSP585 (13.28)	EC_Earth3_veg, SSP126 (5.3)
Length of rainy days	EC_Earth3_veg, SSP126 and SSP245 (45)	ACCESS_CM2, SSP370 (14)	EC_Earth3_veg, SSP245 (60)	ACCESS_CM2, SSP370 (24)

3.7 Projected precipitation changes for the onset, withdrawal and length of rainy days

From the analysis of the results, the best performing CMIP6 GCM for Monsoon onset for Purulia is CanESM5 in the scenario SSP585 and for Ranibandh is CanESM5 in the scenario SSP126. Hence the projected onset days of particular years have been plotted with the selected models only and is shown in Fig. 8. The plot shows that there are regular fluctuations in the onset days of Purulia with days ranging from 108 to 125 days. In Ranibandh, the onset days fluctuations are evident after the year 2060, which ranges from 108 to 137 days. A slight increase in the onset period is observed for both sites, indicating a slight shift of the monsoon period.

For withdrawal, the best performing CMIP6 GCMs for Monsoon Withdrawal are EC-Earth3-veg in the

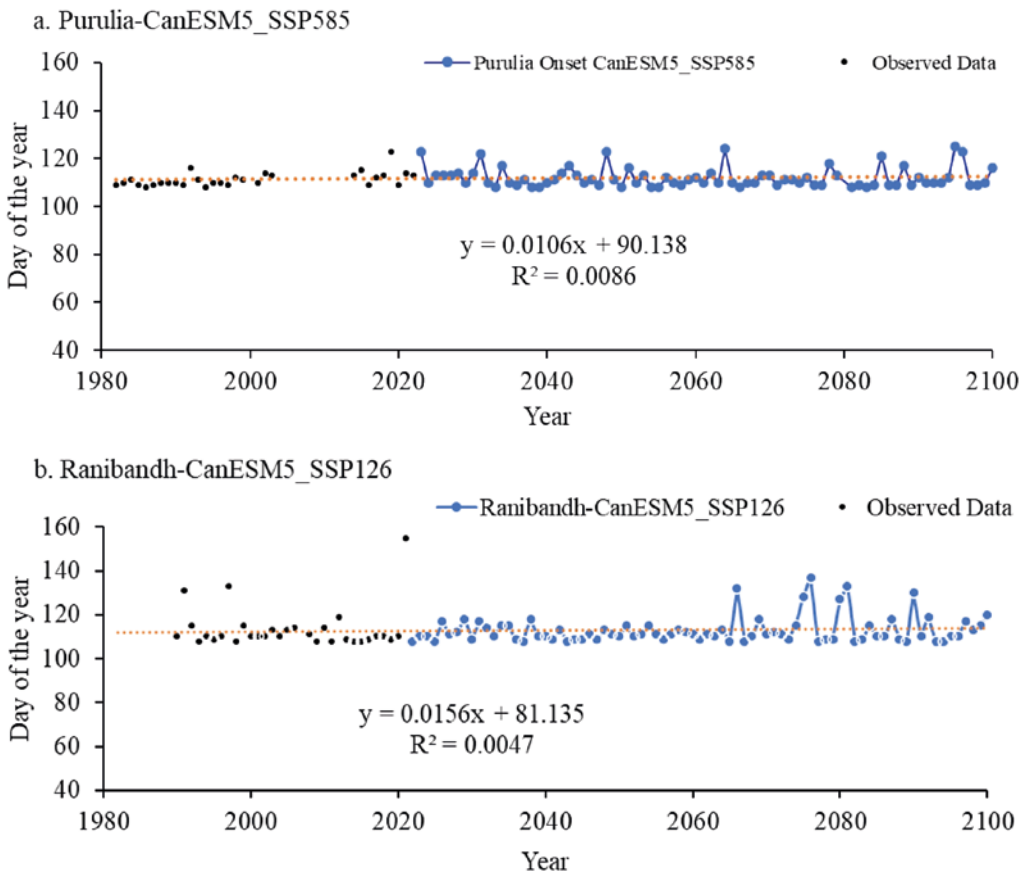

Fig. 8 Plot of onset days for the projected time period 2023–2100 for Purulia and 2022–2100 for Ranibandh locations.

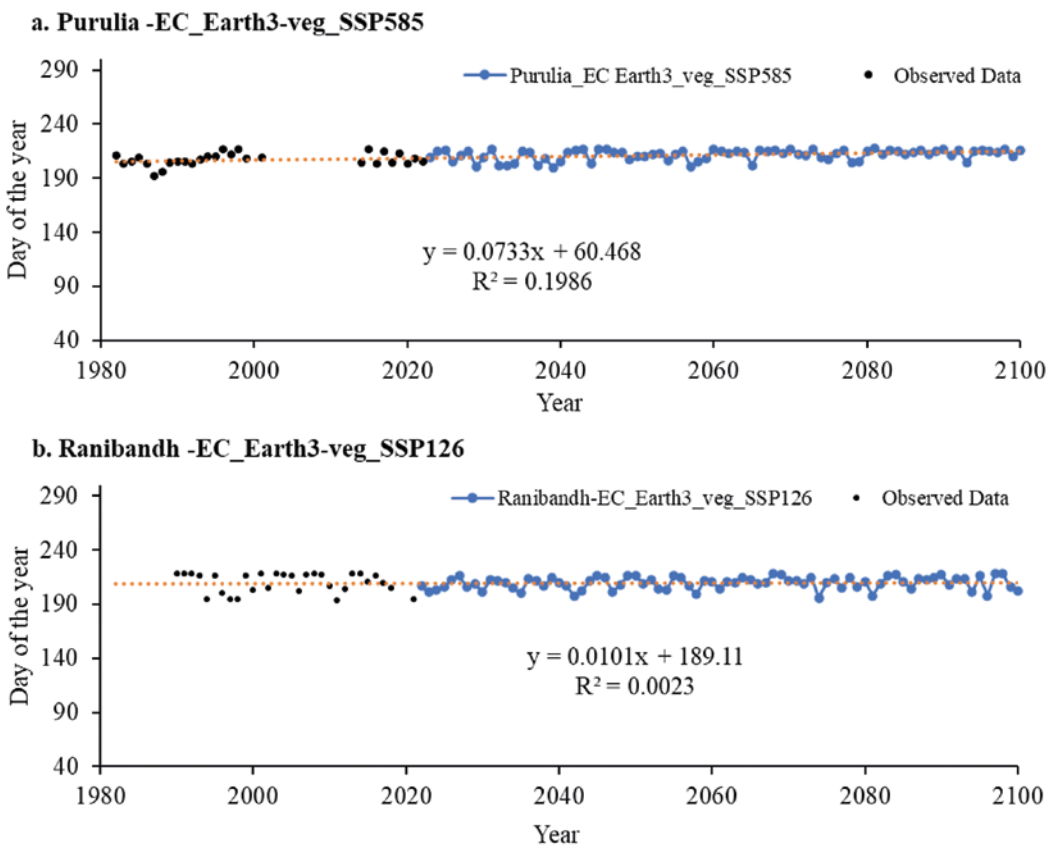

Fig. 9 Plot of withdrawal days for the projected time period 2023–2100 for Purulia and 2022–2100 for Ranibandh locations.

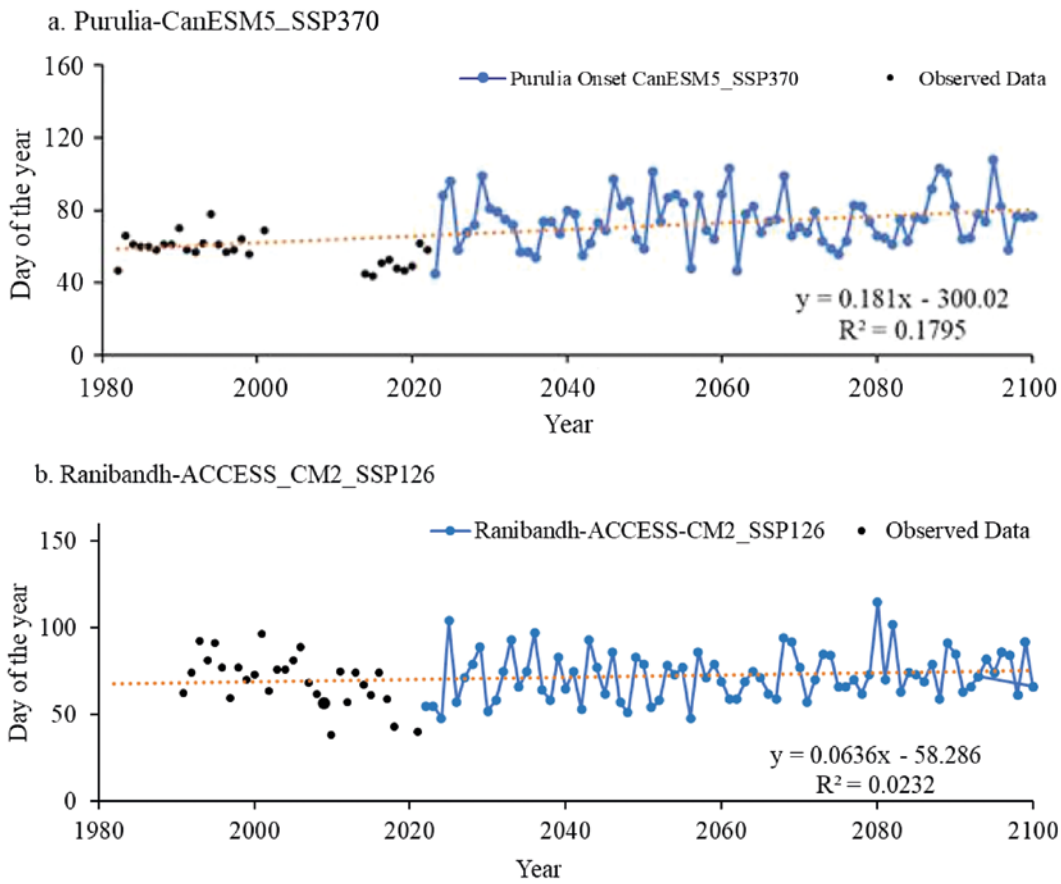

Fig. 10 Plot of number of rainy days in the length of rainy days for the projected time period 2023–2100 for Purulia and 2022–2100 for Ranibandh locations.

scenario SSP585 for Purulia and EC_Earth3_veg in the scenario SSP126 for Ranibandh. As shown in Fig. 9, a slight increase in the withdrawal period is observed for both sites, this indicates a shift of the monsoon period.

From the previous results, it has been observed that the best performing CMIP6 GCM models for number of rainy days in monsoon period are CanESM5 in the scenario SSP370 and ACCESS_CM2 in the scenario SSP126 for Purulia and Ranibandh respectively. The fluctuations are very evident for both stations.

The plot shows that there are large fluctuations in the number of rainy days of Purulia with days ranging from 45 to 108 days. In Ranibandh, also there is large fluctuations in the number of rainy days ranges from 48 to 115 days. From Fig. 10 the overall trend line for number of rainy days is increasing. For Fig. 8, Fig. 9 and Fig 10, the dotted line indicates the trend of datasets of onset days, withdrawal days and the length of rainy days during the time period 1982–2100 for Purulia and 1990–2100 for Ranibandh locations.

4. Conclusions

The comparison of probability density functions (PDF) and cumulative distribution functions (CDF) demonstrates a commendable agreement between observed and modelled rainfall data, highlighting the reliability of models like ACCESS-CM2, CanESM5, and EC-Earth3-veg in capturing rainfall intensity over the study duration. Our findings reveal intriguing patterns in climatological dates for monsoon onset and withdrawal across different climate models. Despite the lack of a coherent spatial pattern in monsoon advancement or retreat, averaging onset, withdrawal, and monsoon season length across all stations facilitates meaningful comparisons against other climate datasets. The nuanced nature of the relationships between observed and modelled data underscores the complexity of climate modelling, with varying degrees of relationship strength identified across different models and scenarios.

For onset, withdrawal and duration of monsoon period, under the scenario SSP585 and SSP126, highest R^2 value of 0.5388 and 0.6370, 0.7539 and 0.5557 and 0.5423 and 0.4560 has been observed for CanESM5, EC-Earth3-veg and ACCESS-CM2 for Purulia and Ranibandh respectively. While for duration of monsoon period between onset and withdrawal, R^2 value of 0.5423 and 0.4560 has been observed for CanESM5-SSP370 and ACCESS_CM2-SSP126 for Purulia and Ranibandh. On the other hand, for Purulia and Ranibandh, the lowest RMSE values has been

observed for the model CanESM5, EC-Earth3-veg and ACCESS-CM2 for onset, withdrawal and monsoon length.

Thus, among the 3 CMIP6 GCM models, the best performing models, i.e the models which exhibit closer agreement with observed rainfall data in simulating monsoon dynamics in the Kangsabati basin for onset, withdrawal and monsoon length, in Purulia and Ranibandh are CanESM5, EC-Earth3-veg and ACCESS-CM2. With these best performing models on projecting the precipitation for 2023 to 2100 for Purulia and 2022 to 2100 for Ranibandh, a very negligible shift has been observed in the onset and withdrawal periods.

The analysis reveals varying relationship strengths between observed and modelled data, emphasizing the significance of these models in capturing onset and withdrawal patterns under different scenarios. Furthermore, the analysis of rainy day duration highlights significant correspondence between observed and modelled datasets, particularly in specific regions and model configurations. However, the variations in R^2 values across different models and scenarios emphasize the need for careful consideration of model performance in different contexts. The visualization of RMSE for monsoon onset, withdrawal, and duration of monsoon period provides valuable insights into model performance. Across all scenarios, discrepancies in the representation of rainfall are evident, with some models displaying higher RMSE values. Conversely, certain models, such as CanESM5, EC-Earth3-veg under the SSP585 and SSP126 scenario, exhibit closer agreement with observed rainfall data in Purulia and Ranibandh, highlighting their effectiveness in simulating monsoon dynamics in the Kangsabati river basin.

Overall, this study contributes to our understanding of rainfall patterns and monsoon dynamics, offering valuable insights for both climate modelling and water resource management in the region. Further research is warranted to refine model outputs and improve our understanding of the complex interactions driving rainfall variability. The future scope of this study includes refining climate models to enhance the accuracy of rainfall simulations and better capture monsoon dynamics. Further exploration of model uncertainty and the integration of observational data could improve confidence in projected rainfall patterns and their implications for water resource management. Engaging stakeholders and fostering interdisciplinary collaboration are crucial for translating research findings into actionable strategies for adaptation and policy development.

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Understanding children's exposure to landslides in Nicaragua

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ABSTRACT

This article evaluates the integration of disaster risk reduction strategies within the educational framework of Nicaragua, with a particular emphasis on children's exposure to landslides and their vulnerability to climate-induced disasters. A comprehensive multi-stage methodology combines geospatial modelling, demographic analysis, and risk assessment to systematically assess landslide susceptibility and its implications for school infrastructure and student safety. The analysis is structured into three distinct phases. The first phase focuses on developing a Landslide Susceptibility Model, utilising historical landslide data along with geophysical parameters to create a robust predictive tool. The second phase entails a geospatial overlay that juxtaposes the identified susceptibility zones with the locations of educational institutions. In the third phase, the analysis centres on the demographic characteristics of children residing in high-risk areas, offering insights into their exposure. The findings identify regions that exhibit elevated risks of landslides, thus posing significant threats to school infrastructure and educational continuity. Moreover, the study highlights the dual role of schools in disaster-prone regions, where they are frequently repurposed as emergency shelters during crises, exacerbating disruptions to education. By integrating geospatial risk assessment with demographic analysis, this research provides a framework for evaluating children's exposure to landslides and calls for incorporating disaster risk reduction strategies into the planning processes of the educational sector.

KEYWORDS

children's exposure; landslides; disaster risk reduction; Integrated Disaster Management; Education-centred approach

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1. Introduction

Landslides represent a recurring and significant geohazard in Nicaragua, particularly exacerbated by the influence of tropical cyclones that induce slope instability through intense rainfall and increased soil saturation (Devoli et al. 2007a; 2007b). The country's mountainous topography, high deforestation rates, and climate variability further amplify the susceptibility to mass movements. This phenomenon disproportionately impacts vulnerable populations, notably children and adolescents.

The consequences of landslides extend beyond immediate casualties and infrastructure destruction; they also disrupt access to education, healthcare, and essential services, exacerbating existing socio-economic inequalities (Burrows et al. 2021; Few et al. 2021). In light of the increasing frequency and magnitude of extreme weather events attributed to climate change, there is an urgent imperative to assess and mitigate the associated risks to children and the educational infrastructure in Nicaragua.

This study seeks to provide an evidence-based understanding of children's landslide exposure by integrating geospatial analysis with demographic and infrastructural data. Specifically, the research develops a landslide susceptibility model for Nicaragua and investigates the spatial distribution of schools in high-risk zones. The study quantitatively assesses the number of schools and children at heightened risk by overlaying the susceptibility map with geospatial data on educational institutions. This analysis aims to inform targeted disaster risk reduction (DRR) strategies. Furthermore, the research contributes to an education-centred, integrated DRR framework by underscoring schools' vital role in fostering risk awareness and enhancing community resilience.

Education plays a critical role in disaster preparedness and the development of resilience, particularly within young populations (Peek 2008). Schools are essential platforms for disseminating DRR knowledge, equipping children with the necessary skills to respond effectively to disasters and fostering an awareness of risk within their communities (Clauss-Ehlers et al. 2004; Mitchell et al. 2009). An education-centred approach to DRR integrates disaster preparedness into school curricula, ensuring that children, educators, and communities are better prepared to mitigate the impacts of environmental hazards (Ruiz-Cortés and Alcántara-Ayala 2020). By analysing the spatial relationship between landslide susceptibility and school locations, this study provides vital insights for policymakers, educators, and disaster management authorities, enhancing the development of risk-informed educational strategies.

The research aligns with global DRR frameworks. It advocates for prospective risk assessment and resilience-building strategies that prioritise children's safety and educational continuity in disaster-prone areas (Sassa 2019, 2020, 2021; Alcántara-Ayala and Sassa 2021). The findings establish a solid foundation for integrating geospatial risk assessment into national disaster management policies. They emphasise the critical necessity of adopting an education-centred approach to enhancing disaster resilience, focusing on the unique challenges developing countries face.

2. Literature review: a general overview

2.1 Climate change-induced displacement and climatic variability: impacts on Children

The projected intensification of climate change, particularly scenarios anticipating a rise of 4 °C or more in global temperatures, poses significant risks of population displacement (Gemenne 2011).

Climate change has caused significant global displacement, affecting about 1.7 billion people through weather-related disasters in the past decade (IFRC 2020; UNICEF 2021). The IDMC projected 30.5 million internally displaced people due to 1,825 disaster situations, with significant displacement in Latin America caused by Hurricanes Eta and Iota, which displaced over 1.6 million individuals (Zuñiga 2022).

By 2050, an estimated 200 million climate-related migrants are expected globally, with over 17 million of these from Latin America, affecting particularly vulnerable children (Brown 2008; Henríquez and García 2023). In Central America, substantial climatic variability has led to increased frequency and intensity of hurricanes, resulting in notable economic and social impacts (ECLAC 2011; Conde and Saldaña 2007).

Climate change disproportionately impacts children's health through climate-induced migration. Children are at increased risk of malnutrition, disease, and psychological harm and often experience violations of their fundamental human rights. More robust global policies are needed to address these health impacts and protect children's rights during migration (Uddin et al. 2021).

Climate change can adversely affect children's mental capacity, particularly in their early developmental years, while access to education remains a significant challenge. During the COVID-19 pandemic, over 13 million children in Latin America and the Caribbean lacked access to remote education, and those in evacuation centres faced difficulties accessing formal education (Zuñiga 2022). Although some studies highlight the long-term impacts of childhood weather disturbances on well-being (Cornwell and Inder 2015), research into children's psychological responses to disasters is still emerging (Lee and Bhang 2018). The complexities of child protection continue to pose challenges at various methodological and conceptual levels (Boyden and Mann 2005).

Nicaragua is particularly vulnerable to climate change, with children comprising 39% of its

population. These children are at heightened risk from extreme weather events, which can lead to landslides and other disasters, disrupting education and displacing families. The compounded effects of poverty, environmental degradation, and social challenges further exacerbate their vulnerability (Boyden and Mann 2005). As reported by IRCI, half of the global child population lives in high-risk countries, with 400 million children exposed to increasing tropical cyclones (UNICEF 2021).

2.2 The role of education in disaster risk reduction

Education is fundamental to disaster risk reduction, especially for children in disaster-prone areas (Apronti et al. 2015). Integrating DRR principles into school curricula helps students understand natural hazards and prepares them to respond effectively. Age-appropriate lessons and activities enhance children's awareness of risks and develop their critical thinking and problem-solving skills (Tomaszewski et al. 2020).

Education is essential for reducing the impact of disasters and enhancing community resilience. Educational programs help raise awareness and promote preparedness. Integrating disaster risk reduction into school curricula and involving local communities in educational initiatives are crucial for effective disaster risk management (Petal 2009).

Community resilience is enhanced by educating children in disaster preparedness and involving them in decision-making processes related to risk management (Clauss-Ehlers et al. 2004; Mitchell et al. 2009).

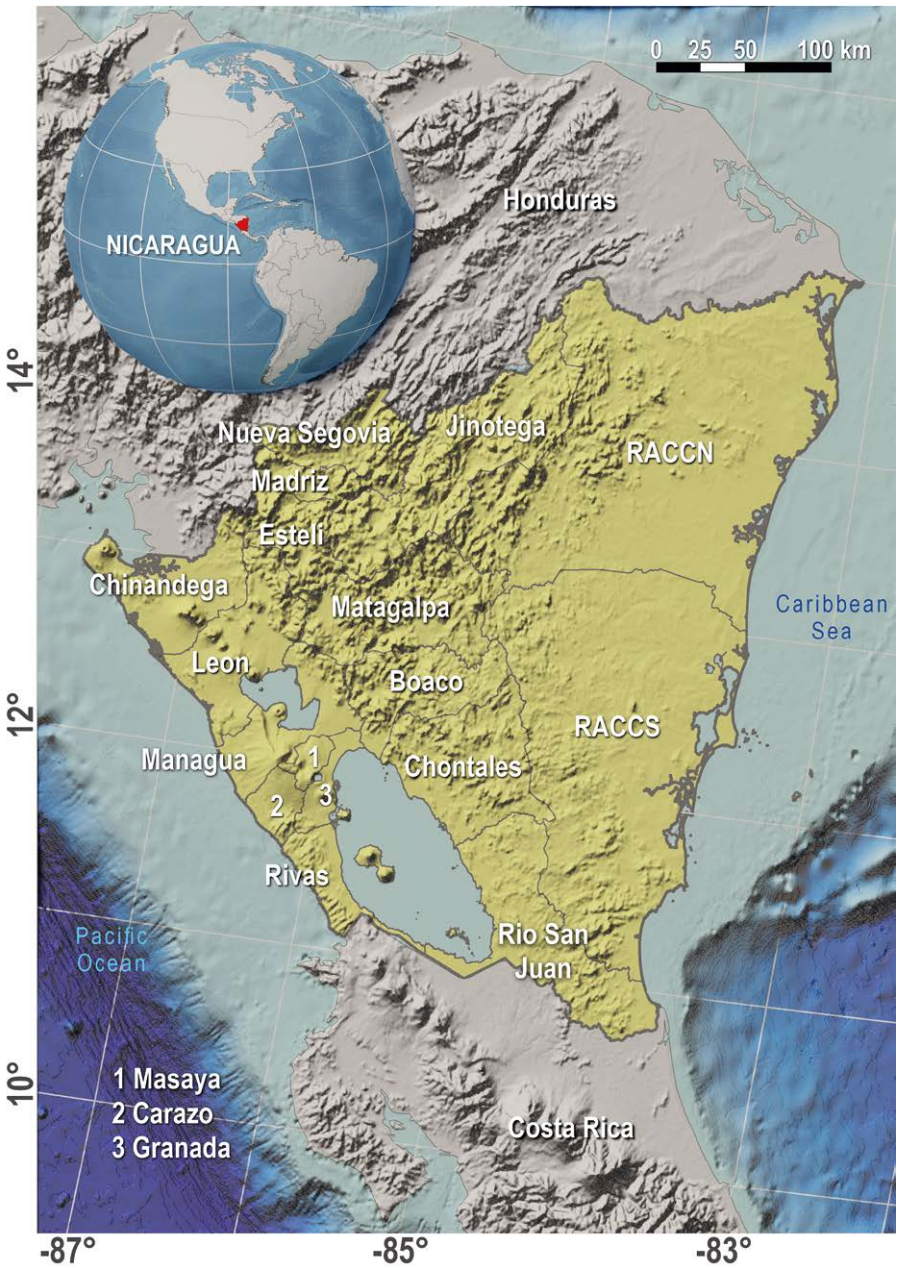

Fig. 1 Location of Nicaragua.

Involving children in DRR initiatives strengthens them and fosters a sense of agency and responsibility (Izadkhah and Hosseini 2005). When children are encouraged to participate in local decision-making processes related to risk management, they become invested stakeholders in their communities' safety and sustainability.

Education in DRR strategies helps mitigate immediate impacts on children and develops a resilient generation (Fernandez et al. 2023). This investment is essential for cultivating informed citizens capable of advocating for and implementing disaster risk reduction strategies (Mitchell et al. 2008).

3. The Nicaraguan context

Nicaragua, situated in Central America, is positioned between latitudes 10° and 15°45′ North and longitudes 79°30′ and 88° West. It shares its borders with the Republic of Honduras to the north, the Republic of Costa Rica to the south, the Caribbean Sea to the east, and the Pacific Ocean to the west (Fig. 1). The nation is politically composed of 15 departments and two autonomous regions: the North Caribbean Coast and the South Caribbean Coast. The total population of Nicaragua is approximately 6,664,364, comprising 3,288,408 men and 3,375,956 women. Of this population, 3,922,596 reside in urban areas, while 2,741,769 live in rural areas. Notably, children aged 0 to 19 comprise 39% of the total population, about 2,604,498 individuals (Fig. 2) (INIDE 2022).

In Nicaragua, most of the population is concentrated in the western region around the capital city of Managua. The coastal areas, especially along the Pacific Coast, have significant population clusters due to their economic roles in trade, tourism, and natural resource management. This uneven population distribution reflects geographic and socio-economic factors influencing urbanisation patterns in Nicaragua (World Bank n.d.).

Light manufacturing, the service sector, and agriculture primarily drive Nicaragua's economy. The country has recently benefited from increased foreign direct investment and remittances, representing 8.3% and 20.6% of its Gross Domestic Product in 2022, respectively. These external financial inflows have played a crucial role in sustaining the country's economic activity and underscore Nicaragua's growing global economic ties (World Bank n.d.).

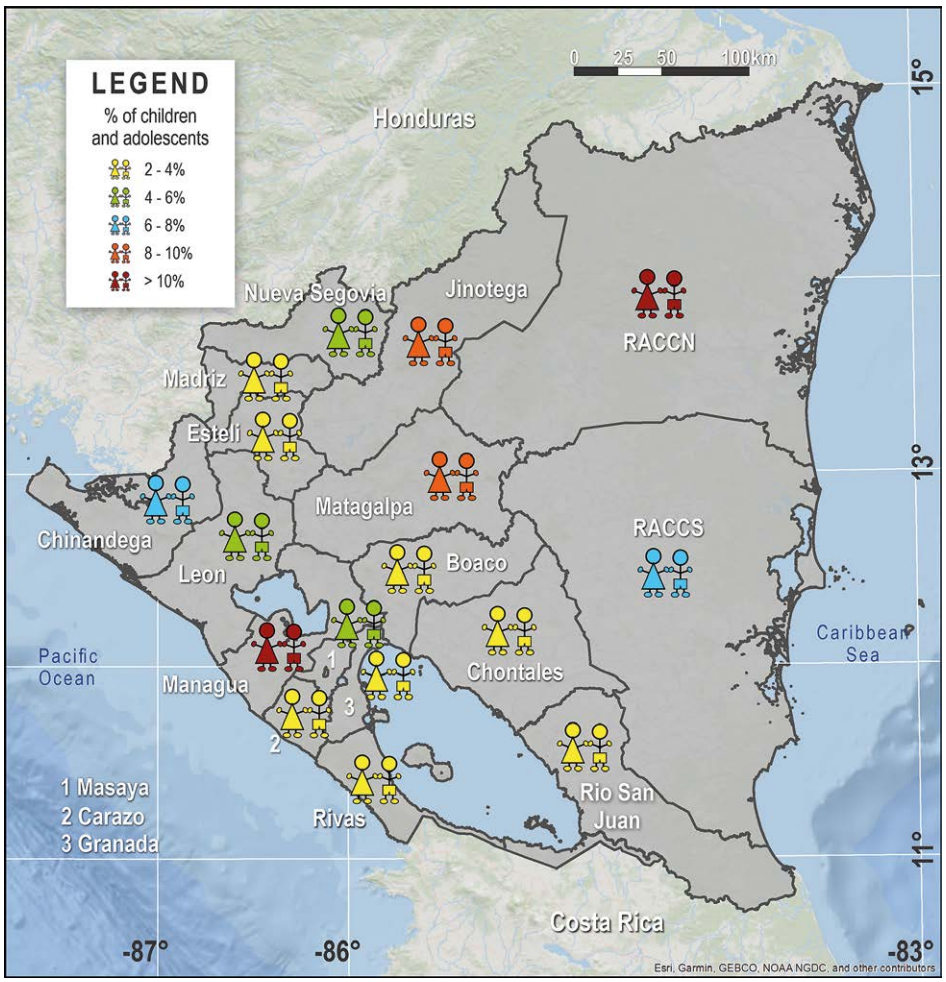

Fig. 2 Percentage of children and adolescents population in Nicaragua by department (Source elaborated with information from INIDE 2022).

Nicaragua faces significant economic challenges and remains one of the poorest nations in Central America. It is highly susceptible to external shocks and frequent disasters, which can disrupt its economic progress. Since 2005, Nicaragua has experienced growing poverty and food insecurity, exacerbated by recent crises. The economy heavily relies on remittances from Nicaraguans abroad, highlighting structural weaknesses in generating employment and income opportunities domestically. International sanctions have restricted Nicaragua's access to foreign capital and limited its ability to attract foreign direct investment, impeding economic recovery and contributing to rising social inequality and financial distress. Nicaragua's path to sustainable development remains precarious due to domestic governance issues and international economic constraints (World Bank n.d.).

Nicaragua's geology exhibits a sophisticated and multifaceted interplay of volcanic, sedimentary, and metamorphic rock formations. It reflects its strategic location within the Central American volcanic arc and the complex dynamics of tectonic plate interactions. Active and dormant volcanoes, including prominent examples such as Masaya, Mombacho, and San Cristóbal, integral to the Nicaraguan Highlands, define the landscape. These volcanic systems play a crucial role in shaping the region's geomorphology and significantly enhance soil fertility, thereby bolstering agricultural productivity across the country. Additionally, Nicaragua's geological diversity is evidenced by extensive sedimentary basins, particularly in its northern and eastern regions, characterised by limestone, sandstone, and shale formations. The Caribbean coastal region further exemplifies this geological complexity, showcasing a dynamic arrangement of limestone and sedimentary rocks that reflects a rich and varied marine environment throughout its geological history (Arengi and Hodgson 2000).

Nicaragua's geological framework can be systematically categorised into five distinct regions, each with unique characteristics. Palaeozoic metamorphic rocks primarily define the Northern Region, which testify to the ancient geological processes that have shaped the area. In contrast, the Central Region, called the Highlands, consists of Tertiary volcanic rocks indicative of more recent volcanic activity. Cretaceous-Tertiary sedimentary formations characterise the Pacific Coast Plain Region, while the Atlantic Coastal Plain Region primarily comprises Quaternary sedimentary rocks, reflecting a younger geological history. Lastly, the Nicaraguan Depression, oriented in a northwest-southeast direction, is notable for its significant deposits of Quaternary volcanic rocks, highlighting the ongoing geological evolution of the region. Collectively, these geological features illustrate the diverse and dynamic nature of Nicaragua's geological landscape, which has profound implications for its ecology, natural resources, and agricultural practices (McBirney and Williams 1965; Kuang 1971; Parsons Corporation 1972; Elming 1998).

4. Methodology

The study employs a multi-stage methodology that integrates geospatial modelling, demographic

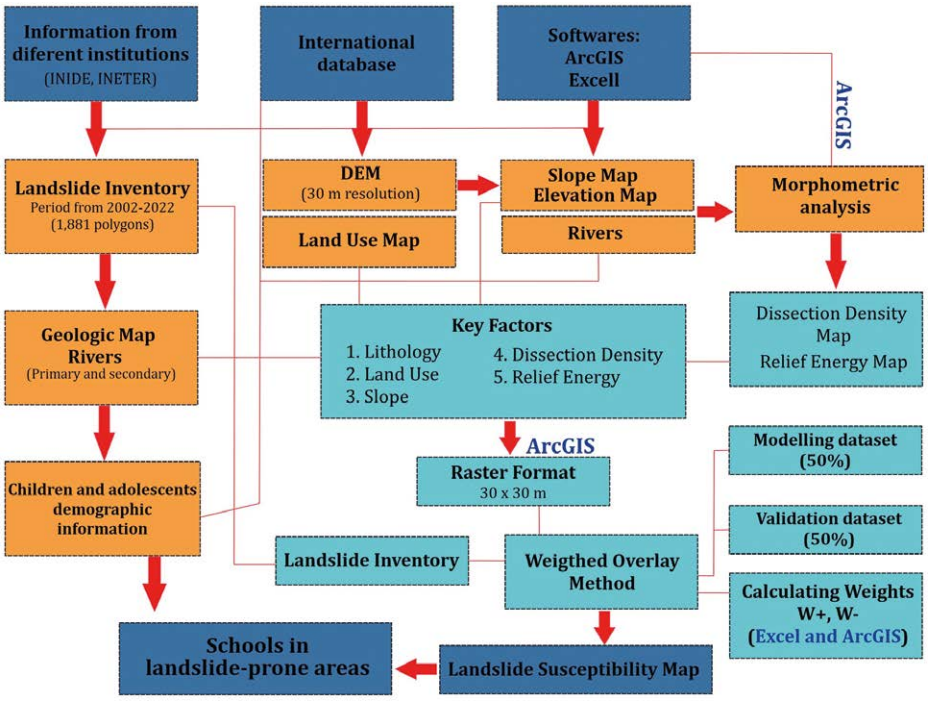

Fig. 3 The methodological framework of the study.

analysis, and risk assessment to evaluate landslide susceptibility and its implications for school exposure (Fig. 3). This approach is structured into three primary phases: (1) the development of a landslide susceptibility map utilising historical landslide data in conjunction with geophysical parameters; (2) the geospatial overlay of susceptibility zones with the locations of educational institutions; and (3) a demographic analysis of the children who are situated in high-risk areas.

4.1 Landslide inventory and data preparation

In the initial phase of the study, a comprehensive analysis of the national landslide inventory was conducted to extract geospatial data relevant to susceptibility modelling. This dataset, obtained from the Nicaraguan Institute of Territorial Studies (INETER), comprises 1,881 polygons representing documented landslide events recorded between 2002 and 2022 (Fig. 4). The inventory provides a spatially explicit representation of past landslide occurrences, serving as a fundamental input for developing and validating the susceptibility model.

The landslide susceptibility model was developed based on five key conditioning factors selected for their well-documented influence on slope instability: relief energy, slope gradient, dissection density, land use, and lithology. Relief energy was derived from a 30-metre resolution Digital Elevation Model (DEM) (Neal and Hawker 2023) and calculated using a hexagonal mesh with a 10 km^2 resolution. This parameter was categorised into six classes: less than 50 metres, 50–200 metres, 200–400 metres, 400–600 metres, 600–800 metres, and greater than 800 metres (Fig. 5A).

Another critical determinant of mass movement susceptibility, slope gradient, was extracted from the same DEM and classified into four intervals: 0–1°, 1–10°, 10–20°, and greater than 20° (Fig. 5B), following the classification scheme proposed by INETER (2003). Dissection density, which reflects terrain incision and fragmentation, was computed from the primary and secondary river networks and categorised into six distinct classes (Fig. 5C).

Land use data were sourced from the 2020 Global Land Cover and Land Use dataset (Potapov et al. 2022) and reclassified into ten categories: forest cover, cultivated land, and urban areas (Fig. 5D). Finally, lithological data were extracted from geological maps (Instituto Geográfico Nacional et al. 1974) and standardised into six major rock types (Fig. 6). These

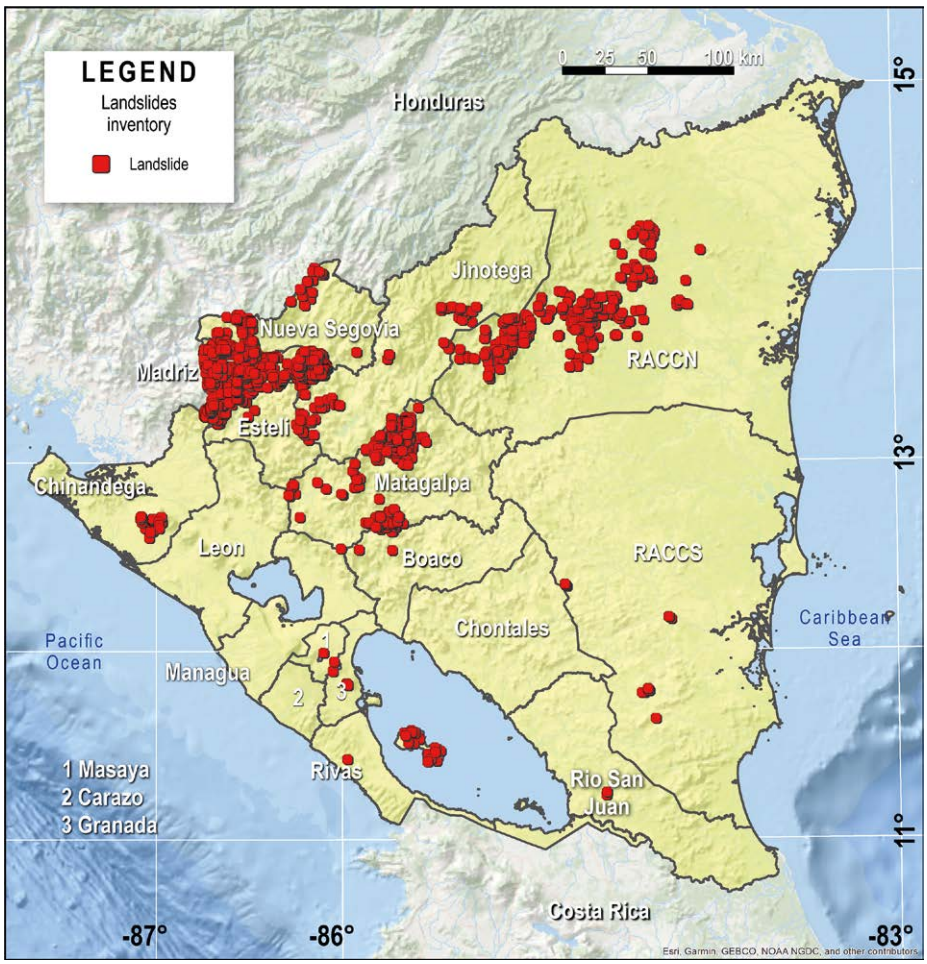

Fig. 4 Landslide inventory (Source: adapted from data provided by INETER).

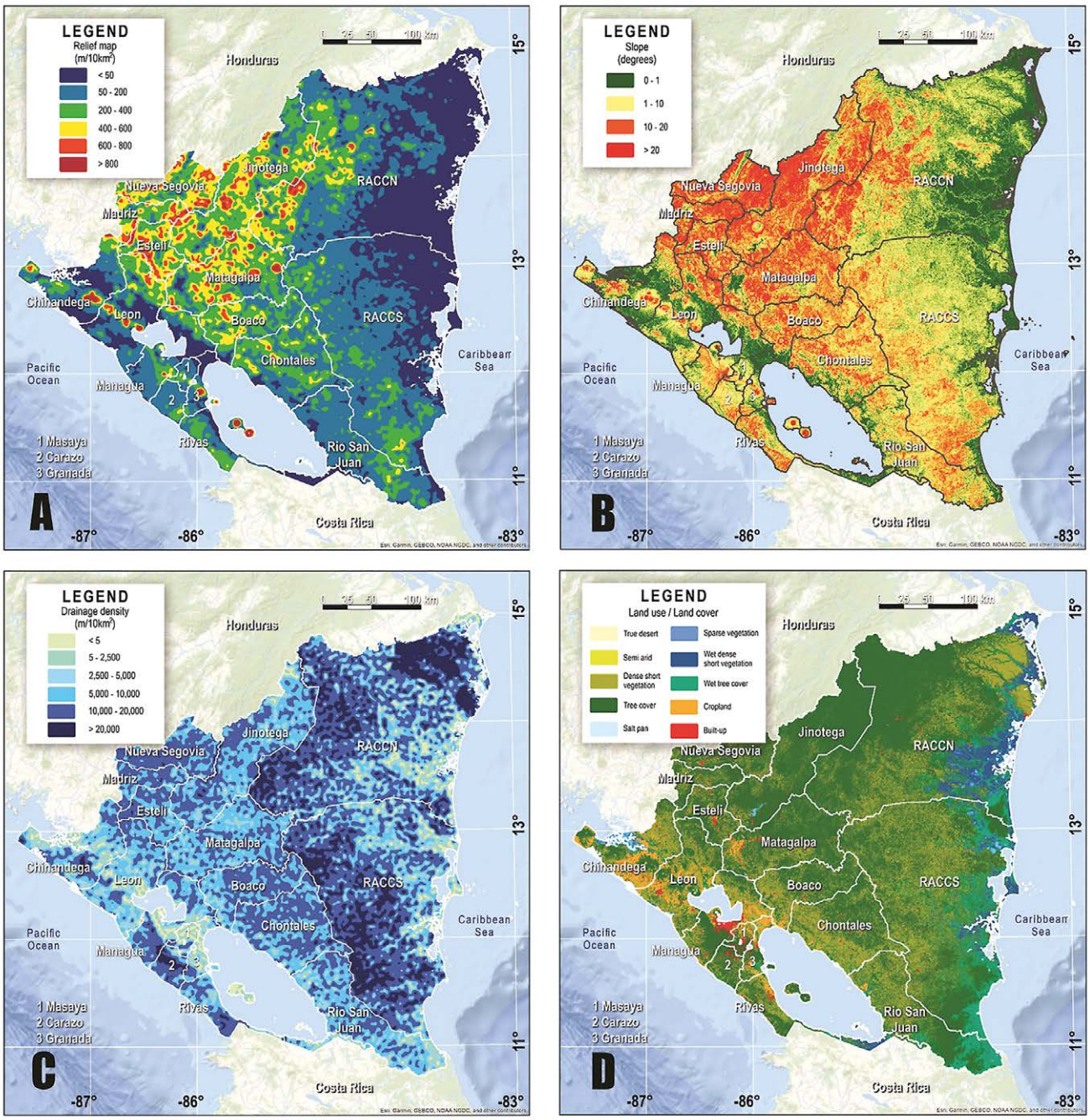

Fig. 5 A. Relief energy map, B. Slope map, C. Dissection density map, D. Land use map.

factors were subsequently rasterised and standardised to a standard spatial resolution, ensuring consistency in the geospatial analysis.

The susceptibility model was constructed using a bivariate statistical approach, specifically the Weight of Evidence (WOE) method, a probabilistic technique based on Bayesian probability theory (Bonham-Carter 1989; 1994). This methodology quantifies the statistical relationship between historical landslides and the selected conditioning factors by computing weight contrast values that indicate the degree of association between each factor and landslide occurrence. The fundamental premise of this approach is that future landslides will occur under conditions similar to those that triggered past events, assuming that the spatial distribution of conditioning factors remains stable over time (Regmi et al. 2010; Oh and Lee 2011; Sujatha et al. 2014).

Implementing the WOE model involved assigning positive (W^+) and negative (W^-) weights to each factor based on its relative influence on landslide occurrence. The weight contrast values were computed and integrated into a weighted overlay analysis using ArcGIS 10.8. Four susceptibility models were generated to assess model robustness, each incorporating different weight contrast values. These models were cross-compared to ensure that variations in factor weighting did not significantly alter the results. The

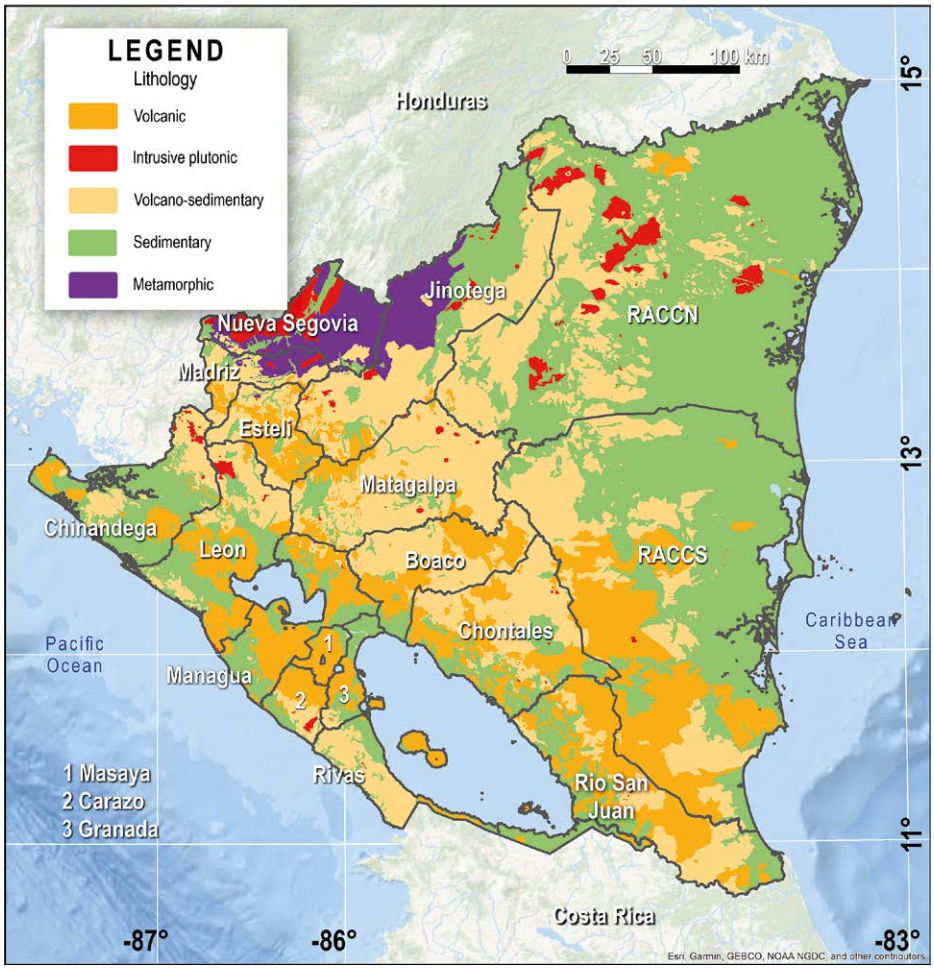

Fig. 6 Lithological map (Source: adapted from Instituto Geográfico Nacional et al. 1974).

final model was selected based on its predictive reliability and stability.

4.1.1 Training and validation of the model

To ensure an objective evaluation of the model's performance, the landslide inventory was randomly partitioned into two equal subsets:

a) The training dataset (940 landslides) was used to establish the statistical relationships between landslide occurrences and conditioning factors.
b) The Validation dataset (941 landslides) was used for independent model testing, ensuring an unbiased assessment of predictive performance.

The independent validation dataset was subsequently overlaid with the predicted susceptibility zones, and model accuracy was evaluated by assessing the proportion of observed landslides that fell within the highest susceptibility zones. The validation results indicated that:

a) 96% of known landslides were located within areas classified as very high susceptibility,
b) 3% were situated in high susceptibility zones,
c) 1% fell within moderate susceptibility zones.

These findings demonstrate the model's high predictive capability and confirm its effectiveness in delineating areas prone to landslides.

The final landslide susceptibility map was produced by integrating the weighted contrast values of all conditioning factors. This map delineates high-risk zones, providing a critical tool for DRR and land-use planning (Fig. 7). The methodological approach applied in this study has been extensively validated in previous research and has been employed in various landslide susceptibility assessments (Lee et al. 2002; Dahal et al. 2008; Lee and Choi 2004; Regmi et al. 2010; Pradhan et al. 2010; Armas 2012; Galindo and Alcántara-Ayala 2014; Sujatha et al. 2014; Getachew and Meten 2021; Bhandari et al. 2024).

Given the high quality of the input data, the robustness of the statistical methodology, and the GIS-based processing workflow, this study's results are considered satisfactory. The final susceptibility map serves as a valuable resource for policy-making and targeted intervention strategies, enabling authorities to prioritise risk mitigation measures in vulnerable regions.

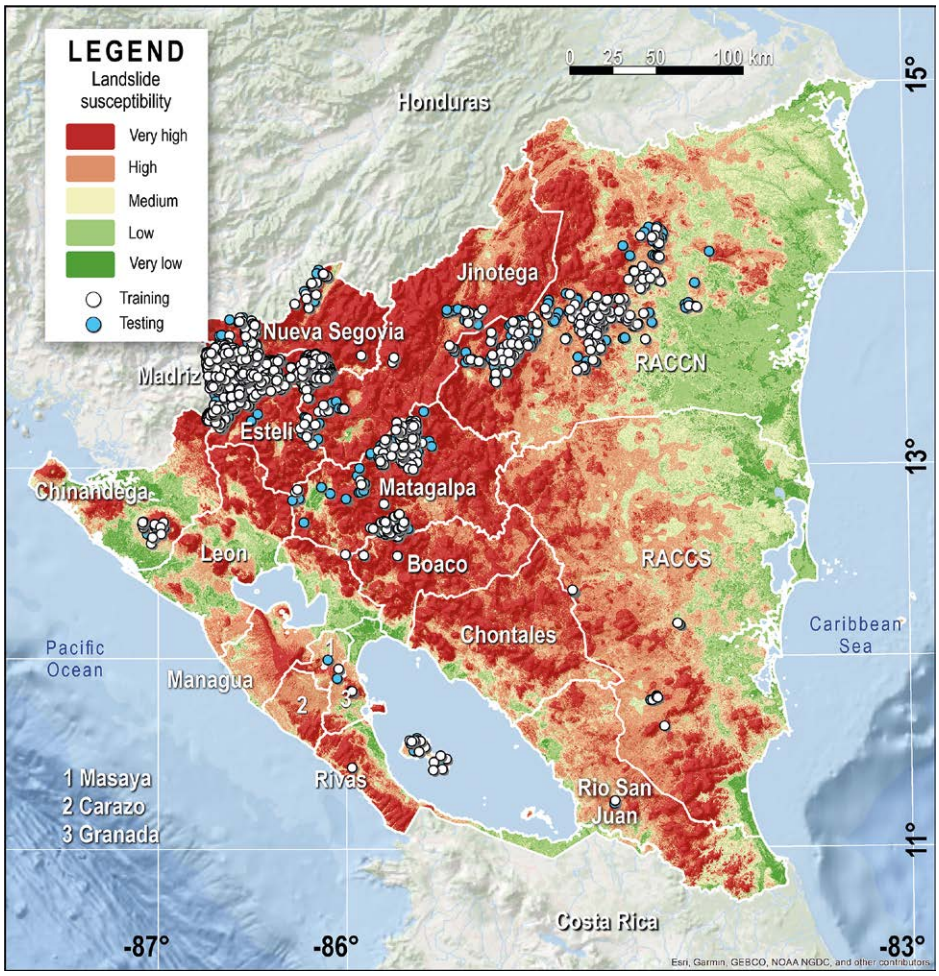

Fig. 7 Landslide susceptibility map.

4.2 Geospatial overlay of susceptibility zones with the locations of educational institutions

In the second phase, the geospatial distribution of schools was analysed to assess exposure within landslide-prone areas. The school database, obtained from INETER (2003), was classified by educational level: Initial Education, Primary Education, and Secondary Education. School locations were verified using Google Maps and Google Earth to ensure spatial accuracy. The susceptibility map was overlaid with school locations, enabling the identification of educational institutions situated within high-risk areas.

4.3 Demographic analysis of children in high-risk areas

The third phase involved demographic analysis to estimate the number of children exposed to landslides. Population data were sourced from national censuses (1971; 2005) and the 2021 statistical yearbook, supplemented by online databases, including Population Density Explorer (https://population-explorer.org) and The Humanitarian Data Exchange (HDX) (https://data.humdata.org). By integrating geospatial school data with demographic datasets, the study quantified the population aged 0–19 residing within landslide-prone areas, providing a comprehensive assessment of children's exposure. Additionally, a literature review of disaster impacts on children, including major hurricanes such as Joan (1988), Mitch (1998), Félix (2007), Eta and Iota (2020), informed the contextual analysis of vulnerabilities (Velásquez and Alcántara-Ayala 2024).

By synthesising geospatial risk assessment with demographic and infrastructural analysis, this methodology provides a robust framework for understanding children's exposure to landslides in Nicaragua. The findings contribute to an evidence-based approach for integrating DRR strategies within the education system, reinforcing the need for proactive risk mitigation measures to enhance community resilience.

5. Results

After creating a landslide susceptibility map, the research analysed demographic data related to

children and educational institutions to identify the spatial distribution of schools within landslide-prone regions in Nicaragua. This analysis aimed to understand the interplay between natural hazards and social determinants, emphasising the need for targeted interventions to support the resilience of young populations.

5.1 Landslide susceptibility map

The factors considered in this research to create the landslide susceptibility map (Fig. 7) were classified into five classes within a GIS, to which weighted values (W^+ and W^-) were assigned. The difference between these two variables was then calculated to evaluate the individual contributions of each factor class to the spatial occurrence of landslides (Tab. 1).

Tab. 1 Classes and weights of conditioning factors.

Conditioning Factors	Classes	$W^+ - W^-$
Lithology	1. Volcanic rocks	−0.4394
	2. Water bodies	−13.6268
	3. Intrusive/plutonic rocks	1.2073
	4. Volcanic-sedimentary rocks	1.2926
	5. Sedimentary rocks	−2.3756
	6. Metamorphic rocks	1.2355
Land Use	1. True desert	−10.8570
	2. Semi-arid	−13.2025
	3. Dense, short vegetation	−0.4733
	4. Tree cover	1.1056
	5. Salt pan	−10.6492
	6. Sparse vegetation	−1.0967
	7. Wet, dense short vegetation	−1.8851
	8. Wet tree cover	−18.2950
	9. Cropland	−16.7154
	10. Built-up	0.6673
Relief Energy	1. <50 m	−19.6126
	2. 50–200	−2.6745
	3. 200–400	0.2448
	4. 400–600	1.6883
	5. 600–800	2.4125
	6. >800 m	2.4533
Slope	1. 0–1°	−19.5116
	2. 1–10°	−1.4473
	3. 10–20°	1.0194
	4. >20°	2.0579
Drainage Density	1. <5 m	−1.6354
	2. 5–2500	−1.9599
	3. 2500–5000	−0.4626
	4. 5000–10000	0.3519
	5. 10000–20000	0.3264
	6. >20000	−0.5201

The slope and relief energy factors significantly contributed to landslide formation. Among the four slope classes, the slope class more significant than 20° exhibits the highest positive weighting, indicating a strong correlation with landslide occurrence. Similarly, in the relief energy factor, the highest positive weightings are observed in classes 5 and 6 (600–800 m and >800 m), where a notable relationship between relief energy and the slope is evident.

Regarding lithology, volcanic-sedimentary rocks (tuff, basalt, ignimbrites), plutonic volcanic rocks (granite), and metamorphic rocks (schists) demonstrate a higher correlation with landslide frequency. Higher weathering and erosion rates make These lithological units more susceptible to landslides. This is further supported by the drainage density data, where classes 4 and 5 show positive weightings for landslides, underscoring the connection between lithology and erosional processes.

Regarding land use, the forest cover class (tree cover) presents a positive weighting. Overall, slope and lithology are the most critical variables influencing landslide frequency in Nicaragua, highlighting their dominant role in landslide susceptibility across the region.

The landslide susceptibility map was generated using the weighted overlay method, which assigns weight values to various factors. The resulting range of weighted values was classified into five susceptibility zones: Very Low, Low, Medium, High, and Very High (Fig. 7). The map reveals that 19% of the territory exhibits Very Low susceptibility, 14% Low, 4% Medium, 30% High, and 33% Very High susceptibility.

The map indicates that landslides are primarily influenced by two key conditioning factors: slope (>20°) and lithology (volcanic and metamorphic rocks). The areas with Very High to High susceptibility are predominantly located in the North-Central region of the country, particularly in the departments of Madriz (notably in the municipalities of Somoto, San Lucas, San Juan del Río Coco, San José de Cusmapa, Telpaneca, and Totogalpa), the North Caribbean Coast Autonomous Region (RACCN) (with a focus on the municipality of Siuna), Matagalpa (in the municipality of El Tuma-La Dalia), and Nueva Segovia (in the municipality of Jalapa).

The susceptibility map is deemed satisfactory based on the quality of the data collected, the method applied, and the GIS processes employed. This outcome is valuable for planning purposes and broad-scale assessments related to integrated risk management.

The model was validated by comparing 50% of the landslide inventory data used for testing. The results demonstrate that the method effectively predicts known and previously unreported landslides. The model's prediction accuracy indicates that 96%

of known landslides occur in high-susceptibility zones, 3% in Medium-susceptibility zones, and 1% in low-susceptibility zones.

Given the limited availability of data on factors such as precipitation, seismic activity, and soil plasticity index in Nicaragua, this analysis's findings are considered satisfactory for a regional-scale study encompassing 130,373 km^2.

5.2 Children and disaster risk: a demographic perspective from Nicaragua

Countries with poor communities are at the most risk of suffering the effects of climate change. These communities are more vulnerable and struggle to adapt to extreme weather events. Children under 14 are 44% more likely to die due to environmental factors in lower-income countries (Bartlett 2009; Ahsanuzzaman and Muhammad 2020).

Like the rest of the countries in the region, Nicaragua has multiethnic, pluricultural, and multilingual particularities. According to INIDE (2022), a population of 6.7 million people is estimated, of which 50.6% are women and 49.4% are men. The urban population is divided into 59%, and the rural population is divided into 41%. The population pyramid base comprises infants and adolescents aged 5–14 (Fig. 8) (INIDE 2022).

According to the Children's Climate Risk Index (IRCI), Nicaragua occupies position No. 94 (low-medium severity), where climate and environmental disturbances are 4.6, child vulnerability is 4.5, and climate and environmental risk of childhood at 4.6 (UNICEF 2021). Also, it is classified among the 5 Latin American countries as highly vulnerable to climate change's effects and lacking the capacity to adapt (Henríquez and García 2023). The Autonomous Region of the North Atlantic has the lowest social indicators in Nicaragua, which is reflected in the quality of the educational infrastructure and the possibilities of access to this service for the school population and its quality (CEPAL, UNDP 2008).

As specified by Bartlett (2009), the most vulnerable population is children under four years of age, which represent 10% of the country's population, because children are in a phase of rapid development and are less prepared to cope with stress because their nervous system is more immature, which has long-term repercussions compared to adults. In Nicaragua, the population under 19 years of age represents around 39.6% of the inhabitants (divided into 20.9% of the urban population and 18.7% of the rural population), exposed and vulnerable to climate change.

The departments with the highest population index in infants and adolescents are Managua with 5,247.76 (7.9%), followed by the Autonomous Region of the Northern Caribbean Coast (RACCN), with 268,261 (4%), then the department of Matagalpa 255,164 (3.8%), the department of Jinotega with 233,963 (3.5%) and finally the department of Chinandega

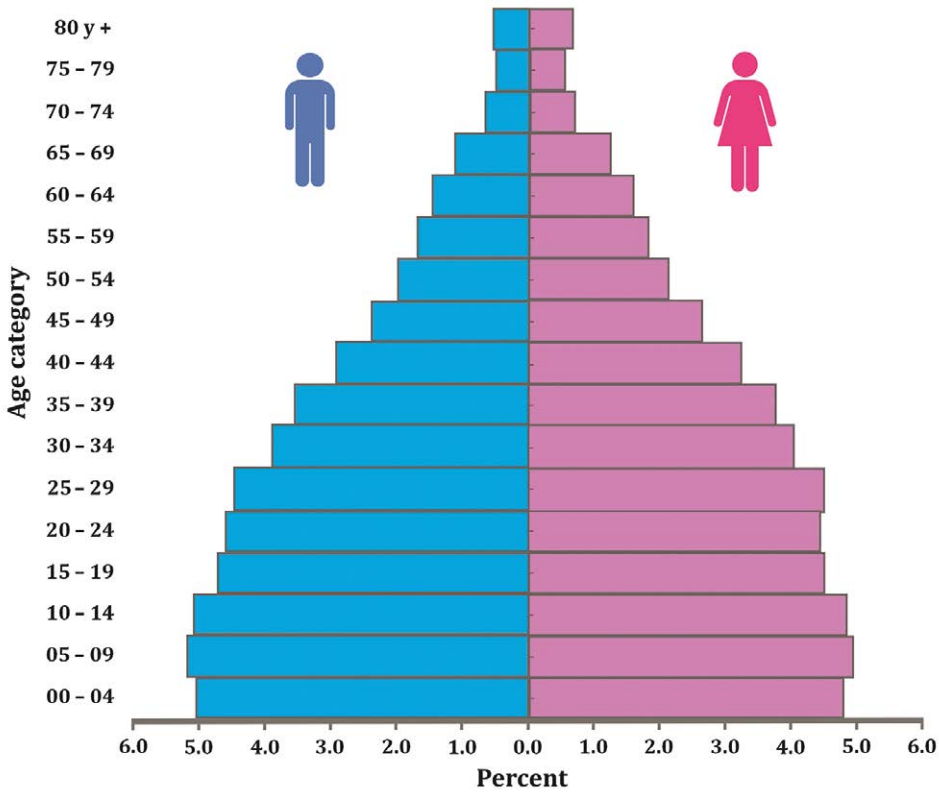

Fig. 8 Estimation and projection of the population of Nicaragua (Source: National Institute of Development Information, INIDE 2022).

with a population of 166,597 (6.4%) of the country's total population (INIDE 2022). These departments were affected by the trajectories of tropical cyclones throughout history, among which the following stand out: Hurricane Joan in 1988, Hurricane Mitch in 1998, which did not impact the Nicaraguan territory directly but caused significant damages, Hurricane Félix in 2007 and finally and in recent years Hurricane Eta and Iota 2020.

5.3 Rainfall-induced landslide disasters: the exposure of children

The education system in Nicaragua comprises 10,185 educational centres distributed throughout the 15 departments and two autonomous regions of the Caribbean Coast (Tab. 2). This system is organised into several levels, including initial education, inclusive special education, primary education, secondary education, and education for youth and adults. Initial education serves as the first level of both basic and secondary education, catering to children aged 3 to 5 years through three modalities: formal, community, and multilevel education. Primary education is designed for children aged 6 to 11, forming part of the basic and secondary education subsystem. Regular secondary education addresses the educational needs of adolescents and young adults between the ages of 12 and 16, taking into consideration their physical, psychosocial, and cognitive development (MINED n.d. [a]).

Tab. 2 Number of educational centres in Nicaragua categorised by department (MINED n.d. [b]: https://serviciosenlinea.mined.gob.ni/mapa-de-la-educacion/Index.aspx).

Department	Number of Educational Centres	%
Chinandega	515	5.1
León	556	5.5
Managua	975	9.6
Carazo	222	2.2
Masaya	235	2.3
Granada	170	1.7
Rivas	236	2.3
Estelí	359	3.5
Madriz	316	3.1
Nueva Segovia	501	4.9
Jinotega	903	8.9
Matagalpa	1098	10.8
Boaco	441	4.3
Chontales	405	4.0
Rio San Juan	467	4.6
RACCN	1251	12.3
RACCS	1535	15.1
Total	10185	100.0

The departments classified as having a very high to high susceptibility to landslides include Madriz, Matagalpa, Nueva Segovia, and the Autonomous Region of the North Caribbean Coast (RACCN). The coverage of educational centres in these regions is notably

limited, with Madriz at 3.1%, Matagalpa at 10.8%, Nueva Segovia at 4.9%, and the RACCN at 12.3%. These educational establishments often experience partial or total disruption due to climatic, socio-natural, and natural hazards. Furthermore, they frequently serve as emergency shelters during disasters, which interrupts educational activities and adversely affects the comprehensive training of students across various educational levels.

Landslides induced by hurricanes and intense rainfall present a significant risk to communities in Nicaragua, particularly with respect to educational infrastructure and the safety of children. The susceptibility of the country's mountainous regions to mass movements is exacerbated by heavy precipitation associated with tropical storms, which often leads to slope instability. The resulting landslides can inflict considerable damage on schools, disrupt educational activities, and pose substantial risks to the well-being of children. During these events, educational institutions frequently serve as emergency shelters, thereby further compromising the continuity of education. Moreover, children in rural and vulnerable urban areas are especially exposed to these hazards, increasing their vulnerability to the immediate and long-term effects of such disasters. Given the high concentration of children living in landslide-prone areas, there is an urgent need for targeted interventions aimed at safeguarding educational infrastructure, ensuring the protection of students, and incorporating disaster resilience strategies into school planning and policy frameworks.

Hurricane Joan, a category 4 Saffir Simpson scale, impacted Nicaraguan territory in October 1988 (Velásquez and Alcántara-Ayala 2023). The hurricane affected the educational infrastructure, damaging 705 classrooms in urban (43%) and rural areas (57%), and the authorities decided to shorten the duration of the school year. Academic activities were interrupted entirely in the Autonomous Region of the Atlantic because some education centres were used as temporary shelters for the evacuated and affected population (ECLAC 1988). The departments directly affected by the path of Hurricane Joan (due to winds with speeds that varied between 232 km/h – 83 km/h) were the Autonomous Region of the Southern Caribbean Coast (RACCS) (Divided in 1971 as Rio San Juan and Zelaya), Chontales, Boaco, Managua, León, Masaya and Granada (Velásquez and Alcántara-Ayala 2024).

According to the 1971 Census, the territory's population was 1,877,952 inhabitants (921,543 men and 956,409 women). Hurricane Joan directly affected 60% of the population, and the total number of

children and adolescents (0–19 years) affected by the direct path of Hurricane Joan was 656,800 (equivalent to 59%) (Tab. 3).

Hurricane Mitch in October 1998 affected the Central American region, and the most significant damage was reported in Honduras and Nicaragua (EIRD and OPS 2000). Although Hurricane Mitch did not directly impact Nicaraguan territory, it caused substantial damage in the country (Velásquez and Alcántara-Ayala 2023). The most affected areas of the country were the departments of Managua, León, Chinandega, Jinotega, Estelí, Nueva Segovia, Madriz and the Autonomous Region of the North Atlantic, Masaya and Granada (ERN Latin America Consortium n.d.; ECLAC 1999).

Tab. 3 Total population between 0 and 19 years that was affected by Hurricane Joan (Source: Executive Office of Surveys and Censuses 1975).

Age range	Total	Urban	Rural
Boaco Department			
00–04	12,260	2,508	9,752
05–09	12,285	2,637	9,648
10–14	10,167	2,451	7,716
15–19	7,169	1,725	5,444
Chontales Department			
00–04	12,895	3,376	9,519
05–09	12,246	3,425	8,821
10–14	10,159	3,082	7,077
15–19	7,221	2,222	4,999
Granada Department			
00–04	11,619	7,064	4,555
05–09	11,810	7,422	4,388
10–14	10,396	6,862	3,533
15–19	7,765	5,328	2,437
Masaya Department			
00–04	15,531	8,114	7,417
05–09	15,370	8,171	7,199
10–14	13,339	7,598	5,741
15–19	9,860	5,806	4,054
Managua Department			
00–04	76,350	61,884	14,466
05–09	76,019	61,396	14,623
10–14	67,069	54,760	12,309
15–19	57,084	47,421	9,663
León Department			
00–04	28,175	12,625	15,550
05–09	28,384	12,779	15,605
10–14	24,477	11,792	12,685
15–19	18,379	9,497	8,882
Rio San Juan Department (RACCS)			
00–04	3,888	795	3,093
05–09	3,695	806	2,889
10–14	2,830	657	2,173
15–19	2,088	610	1,478
Zelaya Department (RACCS)			
00–04	27,235	5,245	21,990
05–09	25,819	5,595	20,224
10–14	20,328	4,946	15,382
15–19	14,888	3,811	11,077

The consequences of Hurricane Mitch stand as one of the most devastating disasters in the region's history. The hurricane's relentless winds and torrential rains precipitated catastrophic flooding and widespread landslides, resulting in an estimated 11,000 fatalities and the displacement of hundreds of thousands of individuals (Cupples 2007). Nicaragua's infrastructure suffered approximately 90% damage, impacting the agricultural sector and leading to economic instability. Around 165,000 people fell below the poverty line, with vulnerable populations experiencing an 18% reduction in assets. Agricultural output declined by 19%, and 20% of healthcare and educational facilities were affected (World Bank 2008). The scale of the disaster revealed deep vulnerabilities in Nicaraguan society's social and economic fabric.

In a widespread disaster, around 2,500 people died due to a mudflow triggered by heavy precipitation from a hurricane. The mudflow occurred on the slopes of Casita Volcano in northwestern Nicaragua, devastating the towns of El Porvenir and Rolando Rodriguez, along with smaller settlements in the low-lying regions. The destructive flow, consisting of water, volcanic debris, and sediment, covered an area of about 12 km^2, leaving it devoid of human life and vegetation (Fig. 9) (Ferraro et al. 1999; Kerle and De Vries 2001).

It was estimated that 52% of the affected population were children with physical damage, orphans, and severe psychological traumas. The interruption

Fig. 9 Casita volcano disaster in western Nicaragua after a mudslide triggered by Hurricane Mitch in October 1998 (Source: United States Geological Survey-Public domain).

Fig. 10 Disaster relief efforts in areas affected by Hurricane Felix in Puerto Cabezas, Nicaragua (Source: U.S. Navy photo by Mass Communication Specialist 2nd Class Todd Frantom-Public domain).

of school activities in several departments had consequences for students' education. It was estimated that 216 schools were destroyed and 296 were partially damaged, with a total of 14.65 million in damages to infrastructure (ECLAC 1999). The estimated losses and damages to educational infrastructure amount to US$21.30 million, while the projected costs for reconstruction are estimated at US$43.3 million (ERN Latin America Consortium n.d.).

Another hurricane that affected the Nicaraguan territory and its population was Hurricane Felix, a category four on the Saffir-Simpson scale. This hurricane impacted the Autonomous Region of the Northern Caribbean Coast (RACCN) with a 259 km/h wind speed in September 2007 (Velásquez and Alcántara-Ayala 2024). The passage of Hurricane Félix completely damaged 58 school buildings and left 57 partially damaged in most of the municipalities of the RACCN (Fig. 10). In addition, most of the damaged infrastructure was primary schools, and classes had to be suspended for two or three weeks. The affected student population was 26,614 people. The damage caused by the disaster in the educational sector reached an amount of 62.3 million cordoba (CEPAL and UNDP 2008). The total population of the country was approximately 5,142,098 inhabitants, where the population directly affected by the path of the hurricane was 314,130 inhabitants of the Autonomous Region of the North Caribbean Coast, of which 185,396 are children and adolescents (0–19 years old) (INEC 2006) (Tab. 4). Hurricane Félix resulted in extensive landslides across the region due to significant rainfall. The departments that experienced the most severe impact included Jinotega, Estelí, Madriz, Nueva Segovia, and the Autonomous Region of the North Caribbean Coast (Consorcio ERN América Latina n.d.).

Tab. 4 RACCN population between 0 and 19 years old affected by Hurricane Felix (Source: National Institute of Statistics and Census, INEC 2006).

Age range	Total	Urban	Rural
Autonomous Region of the North Caribbean Coast (RACCN)			
00–04	51,525	11,473	40,052
05–09	51,214	11,985	39,229
10–14	46,922	12,670	34,252
15–19	35,735	11,311	24,424

Furthermore, Hurricane Félix affected the three main activities that supported the livelihoods of the RACCN population: subsistence agriculture, fishing, and activities related to the use and exploitation of forests (ECLAC 2008).

Other meteorological phenomena that impacted the Nicaraguan territory in November 2020 were hurricanes Eta and Iota, both category four on the Saffir-Simpson scale. In both events, the Ministry of Education (MINED) reported in the municipality of Bilwi and Prinzapolka that 76 schools (63 public schools, 10 subsidised and three private schools) were partially affected; the damage occurred to perimeter walls and the destruction of classrooms. The number of children affected was 7,151 (CODIRECCIÓN – SINAPRED 2020).

The departments directly affected by the path of Hurricane Eta and Iota were the Autonomous Region of the Northern Caribbean Coast (RACCN), Jinotega, Nueva Segovia and Madriz, with winds between 222 km/h – 60 km/h in the case of Hurricane Eta and

Tab. 5 RACCN population between 0 and 19 years old affected by Hurricanes Eta and Iota (Source: INIDE 2022).

Age range	Total	Urban	Rural
Autonomous Region of the Northern Caribbean Coast (RACCN)			
00–04	78,054	20,223	57,831
05–09	70,748	21,257	49,491
10–14	61,744	21,163	40,581
15–19	60,496	21,866	38,630
Madriz Department			
00–04	17,912	5,124	12,788
05–09	18,212	5,522	12,690
10–14	17,848	5,689	12,159
15–19	17,721	5,846	11,875
Jinotega Department			
00–04	64,044	11,349	52,695
05–09	60,372	12,473	47,899
10–14	56,074	13,294	42,780
15–19	54,844	13,687	41,157
Nueva Segovia Department			
00–04	29,448	11,958	17,490
05–09	29,657	12,868	16,789
10–14	29,303	13,474	15,829
15–19	29,229	13,828	15,401

winds between 232 km/h – 74km/h for Hurricane Iota (Velásquez and Alcántara-Ayala 2024).

According to the directly affected departments, the population was 1,476,804 (22% of the country's total). In addition, the total affected population among children and adolescents (age range between 0 and 19 years) was 695,706, equivalent to 26.7% (INIDE 2022) (Tab. 5).

Climatic conditions have been evolving and will continue to do so through changes in temperature and precipitation patterns. Therefore, it is vitally important to understand the impact of these changes on the most vulnerable populations, such as children and poor households. These problems will become more acute as these populations and communities experience continuous changes in climate patterns (Cornwell and Inder 2015).

According to Boyden and Mann (2005), children's vulnerability and psychological resilience depend on factors such as internal strength, health, home dynamics, levels of social support, and how they perceive and interpret experiences. However, the effects of climate change on health will increase inequalities in child health (Helldén et al. 2021).

Added to this, the agricultural populations that are more vulnerable (rural population) in the face of meteorological hazards and households are exposed to having less access to health, food, employment, and education, among others. The absence of effective mechanisms to face decisions in response to disasters puts families in a position to make provisions on what expenses should be reduced, where such decisions can significantly affect children after reallocating resources when assets and income fall drastically (Baez and Santos 2007).

Disasters go beyond normality and the human experience because they cause disturbances and disorders at the personal and family levels and in the community (Boyden and Mann 2005). To improve the aspects of adaptation-preparation-protection-repair and reconstruction at different levels (community, local and regional government), some primary considerations must be considered for an effective response to children and adolescents based on knowledge of the lives and experiences of children, family and community. These measures and actions must be integrated into the planning and decision-making processes at various levels of governance.

In general, countries with impoverished communities around the world face the most significant risk of experiencing the potential impacts of climate change. This does not necessarily imply that climate change will be more extreme in these countries or communities; however, it does suggest that people and the areas they inhabit are more vulnerable, with limited capacity to adapt and prepare for extreme weather events. Among the most vulnerable populations are children, particularly the youngest ones. Children under 14 years of age are 44% more likely to die due to environmental factors compared to the general population. In lower-income countries, the loss of life during phenomena such as floods, hurricane winds, and landslides is disproportionately high among children, women, and older people (Bartlett 2009; Ahsanuzzaman and Muhammad 2020).

5.4 Early findings on landslide risk and the spatial distribution of schools in Nicaragua

The departments categorised within the high susceptibility range for landslides, namely Madriz, Matagalpa, Nueva Segovia, and the Autonomous Region of the North Caribbean Coast (RACCN), are characterised by significant vulnerability to these hazards. The primary economic activities in these regions are predominantly agricultural and tourism-based, reflecting the local populations' reliance on natural resources for their livelihoods. In the case of the RACCN, subsistence fishing and hunting also play crucial roles in the local economy, underscoring the region's dependence on environmental conditions. Notably, the RACCN has the highest population density of children and adolescents, followed closely by Matagalpa.

These demographic trends raise essential concerns, as the socio-economic characteristics of these departments adversely impact household income and restrict access to quality education, particularly in rural areas. Consequently, vulnerable populations, especially children and adolescents, face significant

risks to their health, educational attainment, and overall well-being. This scenario presents formidable challenges in addressing the intertwined issues of poverty, education, and vulnerability to environmental hazards, necessitating urgent interventions to improve the living conditions and prospects for future generations.

The educational infrastructure within these departments includes initial, primary, and secondary education, which is critical for fostering human capital development. Of the total schools included in this study, 14.5% are located in these high-risk departments, with specific distributions as follows: preschool institutions account for 1%, primary schools comprise 6.4%, secondary schools represent 2.5%, and comprehensive educational institutions make up 4.6%. However, these educational facilities frequently experience partial or complete disruption due to climate-related events and socio-natural hazards, such as landslides and flooding. Such disruptions hinder students' academic progress and pose significant barriers to holistic development.

Moreover, many schools are repurposed as emergency shelters during disasters, interrupting regular educational activities and adversely affecting students' psychological and social well-being. This dual function of educational institutions as shelters highlights the urgent need for resilience-building measures that protect educational continuity and community safety in the face of climate change and hazards.

6. Discussion

The analysis of landslide susceptibility and the spatial distribution of schools in Nicaragua reveals critical insights with profound policy implications (Ahsanuzzaman and Muhammad 2020). This study underscores the urgent need for an integrated disaster risk management approach incorporating child-centric strategies, strengthening institutional frameworks, and enhancing educational initiatives. The results highlight that disaster impacts are disproportionately borne by children, particularly in high-risk areas where educational infrastructure is vulnerable to climate-related hazards (Baez and Santos 2007). Consequently, policy interventions must prioritise school safety, community resilience, and proactive engagement with DRR principles.

A comprehensive disaster risk management strategy necessitates coordinating efforts among governmental agencies, local authorities, international organisations, and community stakeholders (Alcántara-Ayala et al. 2020). Given the crucial role of children as agents of change, embedding DRR principles within the education system is fundamental to fostering long-term resilience. Moreover, regulatory frameworks must incorporate child-specific vulnerabilities in risk assessments and disaster response planning. The following policy recommendations address these challenges and ensure a structured, evidence-based approach to disaster resilience.

6.1 Policy implications and recommendations

6.1.1 Advocating for integrated disaster management

To strengthen disaster risk management in Nicaragua, a systematic, integrated approach must be established, prioritising child safety in all disaster planning and response aspects. The following measures are recommended:

- **Develop a National Disaster Risk Management Policy:** Establish a comprehensive regulatory framework delineating roles, responsibilities, and coordination mechanisms among governmental and non-governmental actors (UNISDR 2015).
- **Strengthen Institutional Capacity:** Enhance government personnel's expertise in disaster risk assessment, emergency response, and recovery through structured training programmes.
- **Implement Early Warning Systems:** Develop and maintain reliable early warning systems tailored to local risk profiles, ensuring effective risk communication with communities (UNISDR 2015).
- **Enhance Community Engagement:** Foster participatory disaster planning by integrating local communities into risk reduction strategies, ensuring that Indigenous knowledge and local needs are reflected in policy interventions.
- **Promote Integrated Land Use Planning:** Enforce disaster risk-sensitive land use policies to mitigate vulnerabilities in high-risk areas, particularly regarding school infrastructure and community centres.
- **Allocate Resources for Disaster Preparedness:** Secure sustainable funding mechanisms for preparedness initiatives, including school safety audits, capacity-building programmes, and infrastructure resilience projects.
- **Strengthen Interagency Coordination:** Establish formal collaboration mechanisms between government agencies, NGOs, and the private sector to facilitate cohesive disaster management policies (UNISDR 2015).
- **Implement Regular Drills and Simulations:** Conduct periodic emergency preparedness exercises to enhance response capacities among schools and communities.
- **Integrate Climate Change Adaptation:** Align disaster management strategies with climate adaptation policies, ensuring that resilience-building measures reflect long-term environmental challenges (UNFCCC 2015).
- **Evaluate and Update Policies:** Establish a continuous monitoring framework to assess the effectiveness of disaster risk management policies, incorporating lessons learned and emerging risks.

6.1.2 Strengthening educational initiatives

Given the critical intersection between education and disaster resilience, integrating DRR principles within school curricula is fundamental (Ruiz-Cortés and Alcántara-Ayala 2020). The following policies are recommended to ensure children are equipped with the necessary knowledge and skills to mitigate disaster risks:

- **Integrate Disaster Risk Reduction into School Curricula:** Mandating DRR education in primary and secondary curricula, covering hazards, preparedness measures, and community resilience strategies (Petal 2009).
- **Implement Training for Educators:** Provide targeted training for teachers to equip them with pedagogical tools for effectively delivering DRR education and fostering student engagement (Peek 2008).
- **Develop Age-Appropriate Educational Materials:** Create educational resources tailored to different age groups, ensuring accessibility and comprehension of DRR concepts.
- **Establish School Emergency Response Plans:** Require all schools to develop, test, and regularly update emergency preparedness plans, including evacuation protocols and safety drills (Mitchell et al. 2008).
- **Promote Extracurricular Activities Focused on DRR:** Encourage establishing school-based DRR clubs, competitions, and awareness campaigns to reinforce disaster preparedness knowledge (Izadkhah and Hosseini 2005).
- **Foster Community Involvement in Education:** Strengthen parental and community participation in school-based DRR initiatives to create a culture of resilience at both household and community levels (Fernandez et al. 2023).
- **Implement School Infrastructure Improvements:** Invest in retrofitting and constructing disaster-resilient educational facilities, ensuring schools serve as safe havens during emergencies (Fernandez et al. 2023).
- **Encourage Participation in National DRR Campaigns:** Actively involve students in national and regional DRR initiatives, fostering civic responsibility and proactive engagement in disaster preparedness efforts.
- **Create Partnerships with NGOs and International Organisations:** Leverage expertise and resources from international bodies to strengthen DRR education and school safety initiatives (UNISDR 2015).
- **Evaluate and Adapt Educational Policies:** Regularly assess the effectiveness of DRR education programmes and make necessary revisions based on feedback, technological advancements, and evolving risk landscapes.

6.2 Study limitations

Although this research offers valuable insights, it is important to acknowledge several limitations. These limitations primarily arise from data availability and fieldwork challenges, particularly in developing countries like Nicaragua. The landslide inventory, which serves as a critical foundation for the study, required adjustments for quality assurance. The original dataset, comprising 1,956 records, was refined by unifying lithological categories and removing duplicate polygons, resulting in a final inventory of 1,881 landslides. However, temporal gaps in the dataset, especially before 2002, restricted the study's ability to analyse trends over a more extended historical period. This gap was exacerbated by inconsistent and incomplete records, particularly following Hurricane Mitch. Consequently, the research could not account for potential shifts in landslide patterns over time, which may affect the accuracy of the susceptibility model.

The challenge of field validation further complicated these issues. Nicaragua's rugged terrain, especially in rural and remote areas, rendered on-the-ground surveys highly resource-intensive. Given the limited resources available for comprehensive field validation, corroborating the landslide inventory with real-time data was not feasible. This lack of ground truthing may compromise the reliability of the susceptibility model, as real-time data is essential for verifying the spatial accuracy of historical landslide records.

The use of generalised datasets for land use and geological factors, coupled with outdated demographic data (primarily sourced from the 2021 statistical yearbook), further constrained the resolution of the susceptibility model. While these datasets are often the best available in resource-constrained environments, their coarser spatial detail limits the model's precision. It adds uncertainty to the demographic analysis of children's exposure to landslides. Improved access to high-resolution data, particularly at local scales, would significantly enhance the accuracy of future susceptibility models and enable more detailed risk assessments.

Additionally, limitations in the availability of educational infrastructure data hindered the scope of the research. Information regarding schools, including educational levels (pre-school, primary, secondary), was often outdated or incomplete. This necessitated significant verification using secondary sources such as Google Maps and Google Earth, which may introduce inaccuracies in the spatial data. As a result, the study concentrated on selected departments with more reliable data, thereby limiting the geographic scope of the analysis and reducing the generalisability of the findings. Future research could benefit from efforts to collect more comprehensive, real-time data on educational infrastructure, facilitating a more

robust, nationwide assessment of children's exposure to landslide hazards.

Despite these limitations, this research provides valuable insights into children's exposure to landslide risks in Nicaragua and represents an initial step towards a broader understanding of geohazards in vulnerable regions. As data availability improves and more field validation is conducted, future studies can build upon these findings to offer a more comprehensive analysis of landslide risks and their impacts on children in Nicaragua and similar contexts.

7. Conclusion

Globally, numerous populations face heightened vulnerability to the impacts of climate change, including the elderly, pregnant women, impoverished families, and marginalised groups. Among these demographics, children represent a particularly significant sector, as the repercussions of climate change on their development and well-being can be both profound and enduring. Therefore, it is imperative to implement comprehensive prevention measures, adaptive strategies, and responsive actions that specifically address the effects of climate change on children across various age groups. Prioritising the preparation and education of children for disasters induced by meteorological events, such as tropical cyclones, is essential for their protection and resilience. By fostering effective educational initiatives, stakeholders can strengthen children's agency to comprehend and navigate the risks associated with such phenomena, thereby enhancing their ability to respond to climate-related challenges and ensuring their safety and well-being in the face of an increasingly unpredictable climate.

Historically, Nicaragua has experienced significant impacts from Category 4 and 5 hurricanes on the Saffir-Simpson scale, notably Hurricane Joan (1988), Hurricane Félix (2007), and Hurricanes Eta and Iota (2020). The devastation wrought by these storms has resulted in floods, landslides (Fig. 11), widespread destruction and substantial economic losses, destabilising various departments and municipalities and affecting countless families throughout the country (Velásquez and Alcántara-Ayala 2024). In the aftermath of these catastrophic events, humanitarian organisations have mobilised to provide critical support to the most vulnerable communities impacted by the hurricanes. Such circumstances pose considerable risks to Nicaraguan children and adolescents' health, safety, and well-being, highlighting the urgent need for targeted disaster risk reduction measures and comprehensive support systems to protect this vulnerable population in future emergencies.

Reducing the vulnerability and exposure of children and adolescents to climate-related phenomena is an urgent endeavour, given that these individuals represent potential future leaders at municipal, regional, and international levels (Ruiz-Cortés and Alcántara-Ayala 2020). Equipping them with the necessary knowledge and skills can enhance the resilience of their families, communities, and regions across the country. Furthermore, fostering a heightened perception of risk among children is critical for improving their ability to respond effectively to disasters. Such awareness strengthens them to understand the significance of preparedness in the face of hydrometeorological hazards, including hurricanes, landslides, and floods. Consequently, it is essential to integrate the perspectives and voices of children and adolescents into strategies addressing climate change. Doing so ensures that their insights inform the development of effective disaster risk reduction measures, ultimately strengthening community resilience and promoting sustainable adaptation practices.

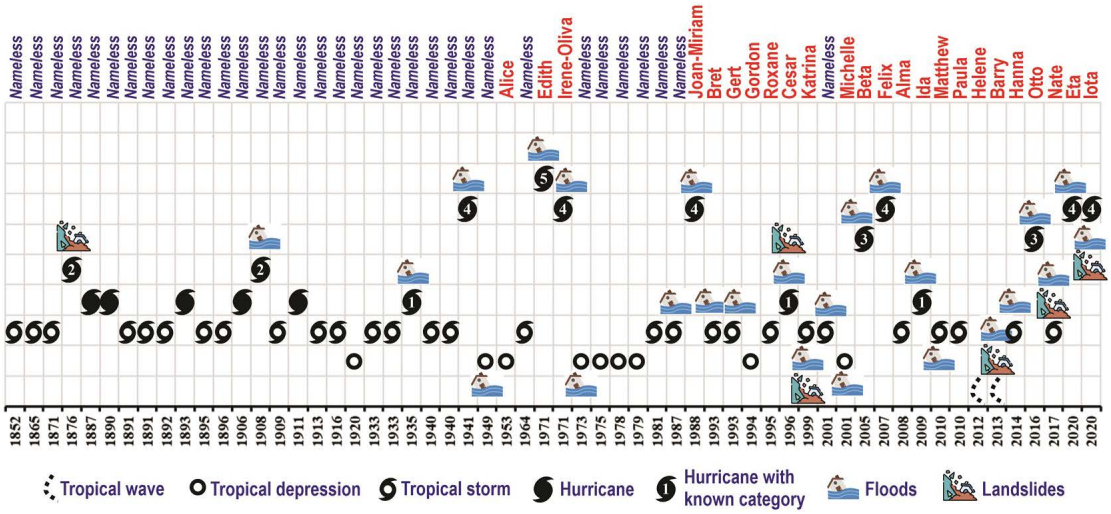

Fig. 11 Tropical cyclones that impacted Nicaragua from 1852 to 2020 and related hazards, including significant landslide disasters (Velásquez-Espinoza and Alcántara-Ayala 2024).

This study underscores the urgent need for evidence-based disaster risk management and education policy interventions. Given the significant exposure of Nicaragua's school infrastructure to climate-related hazards, a multifaceted approach is required – one that integrates institutional reforms, strengthens school curricula and fosters cross-sector collaboration. The proposed policy recommendations provide a roadmap for enhancing resilience through integrated disaster risk management and educational strategies. By embedding DRR principles into national frameworks, Nicaragua can ensure that future generations are prepared for disasters and empowered to contribute to long-term community resilience.

A comprehensive policy response that aligns disaster risk management with educational resilience will safeguard vulnerable populations and foster a culture of preparedness, ensuring that Nicaragua is better positioned to mitigate the adverse impacts of hazards in future years.

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Challenges to cross-border mobility of workers in the EU

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ABSTRACT

This article explores the challenges and opportunities of cross-border labour mobility within the European Union. It aims to systematically assess the key drivers and barriers to cross-border labour mobility and develop evidence-based practical recommendations for improving European Union labour mobility policies. Rapid changes in the labour market due to the COVID-19 pandemic have prompted the adoption of new forms of work organisation, such as remote work and flexible schedules. These changes have created new opportunities to enhance worker mobility, but also present challenges related to coordinating work across different time zones and cultural environments, and ensuring equal working conditions. We analyse the impacts of these challenges on the effectiveness and accessibility of labour mobility within the European Union. This analysis then allows us to formulate practical recommendations for improving the European Union labour mobility policy.

KEYWORDS

cross-border mobility; working hours; flexible work arrangements; cultural differences; legal regulation

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1. Introduction

The topic of cross-border labor mobility within the European Union (EU) has garnered significant academic and policy attention due to its critical role in the broader process of European integration. Scholars and policymakers alike have explored various dimensions of this phenomenon, including its legal, economic, and social implications. In the process of European integration, the realization of social rights initially played a minor role. The EU member states focused on economic development and introduced four basic economic freedoms: freedom of movement of goods, services, persons, and capital. These freedoms were supposed to ensure an open market economy with free competition (Semihina et al. 2022).

Enshrining the free movement of workers as the basis of the European economic integration association was made possible by understanding how wages and working conditions in different member states affect the capabilities of the internal market. These conditions are an important component of the cost of goods and services (Rym 2019). The competition of social norms between Member States on wages and working conditions promotes competition between employees for better conditions, which can be used as an instrument of economic pressure. Harmonization of legal protection of employment at the European level has been recognized as a prerequisite for building an effective EU internal market. As a result, the free movement of workers across the EU was recognized as an important economic freedom that contributed to further social, economic and political integration (Oliynyk 2019).

In today's context of globalization and integration of European markets, the issue of cross-border employee mobility is of particular importance. Cross-border workers within the EU are defined as EU or EFTA nationals who reside in one EU or EFTA country and work in another, performing their work duties as employees or self-employed persons. Cross-border workers therefore cross borders regularly or irregularly to perform their work. This category may include legally defined groups of workers, in particular seasonal workers and frontier workers (Directorate-General for Employment, Social Affairs and Inclusion and European Commission 2023). However, it is important to distinguish between cross-border mobility and long-term labour mobility, which involves workers moving within the EU for a longer period to work in another country.

In addition, it is worth noting the specificities of posted workers, who are an important category within the European labour market. Posted workers temporarily perform work in another EU Member State, while remaining in an employment relationship with their employer from their country of origin. Directive 96/71/EC and its amendment 2018/957/EU define the working conditions for this category of workers, in particular regarding pay, working hours and social protection (European Parliament and Council of Europe 2018).This distinction is important for understanding the complexity of labour mobility processes within the EU and the need to develop policies that take into account the different forms of mobility, including short-term and long-term movements of workers, as well as the working conditions of posted workers.

Cross-border mobility of employees is the process of moving labor between countries in order to fulfill their employment duties. In the context of the European Union, this term means the free movement of workers between member states. The Treaty on the Functioning of the European Union contains a provision implementing the free movement policy (Consolidated version of the Treaty on the Functioning of the European Union 2012). This principle ensures the right of every EU citizen to work in another member state without restrictions related to nationality or residence.

Cross-border mobility contributes to economic growth and development by enabling employers to find skilled workers and workers to access a wider labor market (Barslund and Busse 2016). However, despite its significant benefits, this process is also accompanied by a number of challenges, such as differences in legal regulations, work cultures, and working conditions. Changes in working hours and work organization, such as the introduction of flexible work schedules and remote work options, are creating new opportunities for employees that contribute to their mobility. These changes are particularly relevant in the context of the COVID-19 pandemic, which has forced many companies to rethink their approaches to work organization (Bruurs 2023). However, such changes can also make it difficult to coordinate work processes between employees from different time zones and cultural backgrounds, which requires additional analysis and recommendations to overcome.

In addition, different working cultures in EU member states may affect employee performance and adaptation to new working conditions. Employers face the challenge of integrating employees with different approaches to working hours, which can lead to conflicts and reduced productivity. Analyzing these aspects and developing recommendations to overcome them is an important step towards improving working conditions and increasing the EU's competitiveness on the global stage. Research on this topic will help to understand how to optimize work processes and facilitate effective cross-border mobility of workers in the European Union.

2. Methodology

This study adopts an interdisciplinary approach, encompassing legal and social aspects of cross-border labor mobility within the European Union.

A comprehensive analysis of legal documents, academic literature is employed to explore the topic. The data collection process for this study was multi-faceted, drawing from a range of sources to ensure a comprehensive understanding of the topic. First, an extensive review of EU regulatory frameworks was conducted. This included examining key regulations and directives that directly influence cross-border labor mobility. These documents were analyzed to understand the legal context and the specific provisions that affect the movement of workers across EU borders.

In addition to EU-level regulations, the study also delved into national legislation from various EU member states. This was crucial for understanding how different countries interpret and implement EU directives and regulations in their domestic legal systems. The national laws were selected based on their relevance to labor mobility, such as laws governing working hours, social security coordination, and employment contracts. By examining these laws, the study aimed to identify both commonalities and differences in national approaches, which could influence the ease or difficulty of cross-border labor mobility.

The data analysis phase of this study involved a qualitative content analysis, aimed at identifying key themes and patterns related to cross-border labor mobility. The first step in this process was to systematically code the legal texts, academic literature, and statistical reports. This involved breaking down the documents into manageable segments and tagging them with relevant codes that represented various aspects of labor mobility, such as regulatory barriers, economic incentives, or social challenges. This coding process allowed for the organization of data into meaningful categories, facilitating a deeper understanding of the complex factors influencing labor mobility.

To ensure clarity of the analysis, the following codes were used: *legal regulation* (EU regulations, national laws), *working hours* (difference in duration, flexible schedules), *time zones* (work coordination, impact of time differences), *working cultures* (employee adaptation, cultural barriers).

Once the coding was complete, the next step was to perform a thematic analysis to identify recurring themes and significant findings across the different data sources. Key themes included the impact of differences in national regulation, the role of the EU directive in practical harmonisation, the socio-economic consequences of mobility and the importance of cultural adaptation. These themes were further analysed to understand their interrelationships and their relevance to the larger context of labour mobility in the EU.

In addition to thematic analysis, a comparative legal method was employed to contrast the regulatory approaches of different EU member states. This involved comparing national laws on key issues such as working hours, social security, and employment rights, and analyzing how these differences might affect cross-border mobility. The comparative analysis was particularly useful for identifying potential legal barriers to mobility and understanding how different countries balance national interests with EU obligations. This method also highlighted best practices that

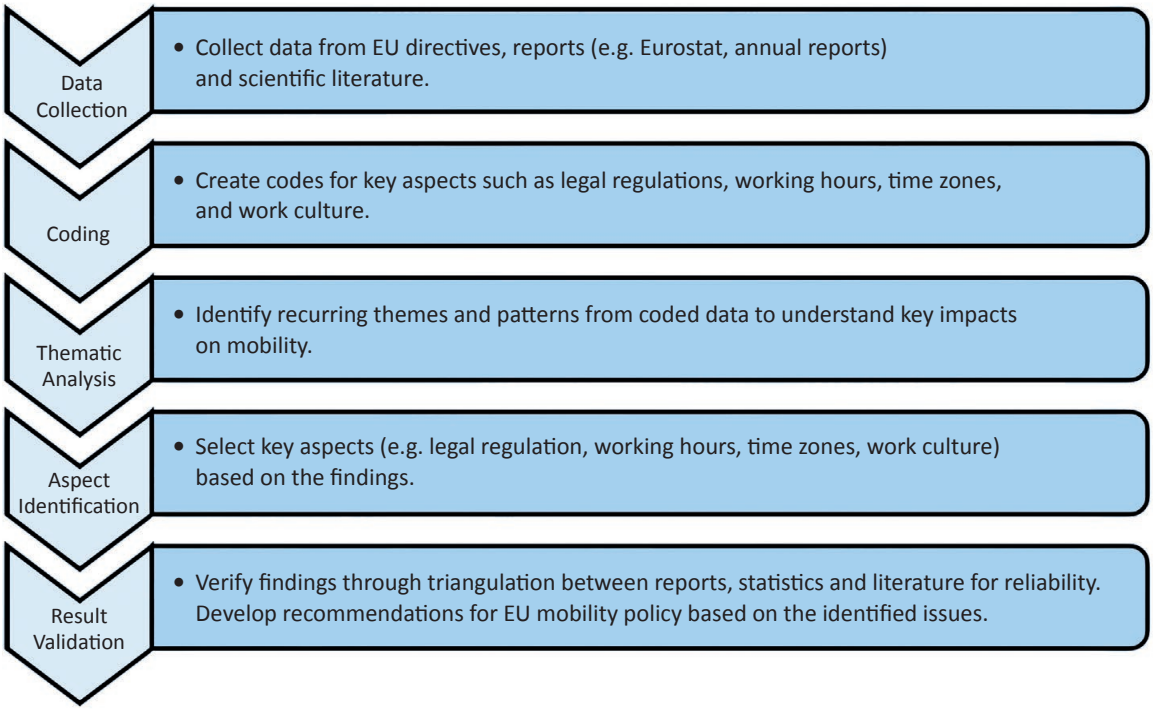

Fig. 1 Research methodology for EU mobility policy analysis.

could be adopted by other member states to facilitate labor mobility.

Finally, the study engaged in a critical analysis of the data, questioning assumptions and considering alternative interpretations of the findings. This step was crucial for ensuring that the analysis was not only descriptive but also analytical and interpretative. By critically examining the data, the study aimed to provide insights that go beyond surface-level observations, offering a nuanced understanding of the challenges and opportunities associated with cross-border labor mobility in the EU. This comprehensive approach to data analysis ensured that the study's findings were robust, well-supported by evidence, and relevant to both policymakers and scholars.

In this study, the author used many analytical reports, which, among other things, included statistical data. In particular, the annual reports of the European Commission, Eurostat data and analytics of international organizations were analyzed. The author identified and analyzed a number of indicators, including the number of cross-border workers; employment levels in different EU member states; working week duration; data on social protection. The collected data were systematized and presented in the form of tables and plans for further analysis. Statistical information served as the basis for identifying key features in the field of cross-border mobility of workers (Fig. 1).

The limitations of this study include the lack of access to some primary data and statistical information, which could provide a more precise understanding of the situation. Furthermore, the study primarily focuses on the analysis of the legal framework and does not fully address socio-cultural aspects that may also influence cross-border labor mobility. The results obtained can be used to enhance EU policy in the field of labor mobility, as well as to develop recommendations for member states on optimizing national policies in this area.

3. Literature review

The legal foundation for cross-border labor mobility in the EU is grounded in the Treaty on the Functioning of the European Union (1957), which establishes the free movement of workers as one of the fundamental freedoms. Key legal instruments, such as Directive 2004/38/EC (European Parliament and Council of Europe 2004a) on the right of EU citizens to move and reside freely and Regulation (EC) No 883/2004 (European Parliament and Council of Europe 2004b) on the coordination of social security systems, are crucial in ensuring that workers can exercise this right while maintaining their social protection across borders. Scholars have emphasized the importance of these legal frameworks in facilitating labor mobility while protecting workers' rights. For instance, Mörsdorf (2012) discusses the legal mobility of companies and its impact on workers' rights within the EU, highlighting the role of EU-wide regulations in harmonizing employment conditions across member states. Similarly, Medeiros (2019) explores the challenges of cross-border mobility in EU border regions, particularly in terms of legal and social security coordination.

A comprehensive view of cross-border labor mobility was also highlighted. Barslund and Busse (2016) argue that labor mobility is essential for the functioning of the single market, as it allows for a more efficient matching of labor supply and demand across different regions. However, they also note the challenges posed by disparities in wages, working conditions, and social security systems among member states. Other studies, such as those by Rym (2019), emphasize the potential benefits of labor mobility but also highlight the risks of social dumping. These findings are complemented by Dowlah (2020), who offers a historical and contemporary perspective on cross-border labor mobility, highlighting its evolution and current research for globalized labor markets. Other studies, such as Rome (2019), emphasize the notable benefits of labor mobility, but also highlight the risks of social dumping, when workers face declining working conditions due to competitive pressures.

The cultural and social aspects of cross-border labor mobility are also well-documented in the literature. Hofstede's (1980) cultural dimensions theory has been widely applied to understand how national cultures influence labor practices and organizational behavior in different EU countries. For example, differences in power distance, individualism versus collectivism, and uncertainty avoidance can impact how workers from different cultural backgrounds adapt to new working environments (Cîmpeanu and Pîrju 2010). Studies by Steindl and Jonas (2012) and Nakonechna (2024) further explore the challenges of cultural adaptation in cross-border mobility, highlighting the role of cultural differences in shaping workers' experiences and integration into new workplaces. These studies underscore the importance of cultural sensitivity and the need for tailored support mechanisms to help workers navigate the complexities of cross-cultural interactions in the workplace.

The rise of flexible work arrangements, particularly in response to the COVID-19 pandemic, has introduced new dynamics into the discourse on cross-border labor mobility. Research by Tang et al. (2011) and Sivunen et al. (2016) examines the impact of time zone differences on global collaboration, noting that while flexible work schedules can enhance mobility, they also pose significant challenges for coordination and communication within multinational teams. Prychepa et al. (2018) and Watson-Manheim et al. (2012) provide further insights into how organizations can manage these challenges, emphasizing the importance of effective time management, clear

communication protocols, and the use of digital tools to bridge the gaps created by time zone differences. These studies highlight the need for organizations to develop strategies that support workers in maintaining a healthy work-life balance while adapting to the demands of flexible and remote work arrangements.

The literature on cross-border labor mobility in the EU provides a rich and diverse understanding of the factors that influence this phenomenon. While the legal and economic frameworks are well-established, ongoing research continues to explore the cultural and organizational challenges that arise in the context of increasing labor mobility. The synthesis of these perspectives underscores the complexity of cross-border labor mobility and the need for a multifaceted approach to policy development that takes into account the legal, economic, cultural, and social dimensions of this issue. Further research is needed to address the emerging challenges posed by flexible work arrangements and to develop best practices for managing a diverse and mobile workforce within the EU.

4. Results

4.1 Legal regulation of cross-border mobility of employees in EU legislation

Cross-border mobility of workers is a key element of European integration and one of the fundamental principles of the European Union. Free movement of workers contributes to economic growth, social integration and equal opportunities for all EU citizens (Mörsdorf 2012). However, in order to ensure effective mobility of workers, it is necessary to create an appropriate legal framework that regulates all aspects of their movement, employment and social protection (Medeiros 2019). In this context, the main EU regulations and directives play an important role. In Tab. 1 below, we provide a brief overview of the main legislation. This list is not exhaustive, but includes those documents that, in our opinion, are most important for ensuring effective labor mobility in the EU. These legal acts provide a comprehensive legal framework for regulating all aspects of movement, employment and social protection of workers within the EU, ensuring harmonization of social standards and promoting a level playing field for all labor market participants.

The legal acts regulating this process play a key role in ensuring effective mobility and protecting workers' rights. An analysis of the main documents shows how important it is to ensure legal protection for workers moving between EU member states. Each of these legal acts is aimed at regulating certain aspects of cross-border employee mobility. In general, EU legislation creates a comprehensive and interconnected legal framework for ensuring effective cross-border mobility of workers. It regulates all aspects of this process, from the right to free movement to working conditions and social security, which provides workers with the necessary protection and support.

Tab. 1 Key legal acts regulating cross-border mobility of workers within the European Union.

Legal act title	The main point	Regulation of cross-border mobility of Workers	Significance for Workers
Treaty on the Functioning of the European Union 1957	Foundational document of the EU, establishing the legal framework for its functioning.	Guarantees the freedom of movement for workers within the Union.	Establishes the legal basis for the free movement of workers.
Directive 2004/38/EC	Regulates the rights of EU citizens and their families to move and reside freely.	Establishes the right to enter and reside for up to three months, and the right to permanent residence after five years.	Ensures social integration and access to the labor market.
Regulation (EC) No 883/2004	Coordination of social security systems.	Coordinates social security systems to ensure continuity of social protection.	Protects social rights of workers when moving between Member States.
Directive 96/71/EC	Working conditions for posted workers.	Establishes minimum working conditions and employment terms for posted workers.	Protects the rights of workers temporarily posted in another Member State.
Regulation (EU) No 492/2011	Freedom of movement for workers within the EU.	Ensures equal access to employment and equal treatment of workers from other Member States.	Guarantees equal employment opportunities.
Directive 2014/54/EU	Measures to facilitate the free movement of workers.	Defines measures to support and protect the rights of workers exercising their right to free movement.	Supports workers' rights and facilitates their mobility.
Regulation (EU) No 2016/589	European Employment Services (EURES).	Establishes the EURES network to facilitate worker mobility within the EU.	Supports job search and employment in different Member States.
Directive 2018/957/EU	Amendments to Directive 96/71/EC on posting of workers.	Enhances rules for posted workers, particularly regarding pay and working conditions.	Increases protection for posted workers.

Source: European Parliament and Council of Europe (1997; 2004a; 2004b; 2011; 2014; 2016; 2018).

4.2 Differences in working hours between Member States and their impact on cross-border mobility

Working time in the European Union is regulated by both national legislation and European directives that set minimum standards. The main legal act at the EU level is Directive 2003/88/EC of the European Parliament and of the Council of 4 November 2003 concerning certain aspects of the organization of working time, which establishes general principles on maximum working hours, minimum rest periods and other aspects related to the organization of working time. Directive 2003/88/EC stipulates that the maximum working week in the EU should not exceed 48 hours, including overtime. In addition, employees are entitled to a minimum of 11 hours of uninterrupted rest per day and a minimum of 24 hours of uninterrupted rest per week. The Directive also sets minimum requirements for annual paid vacation, which must be at least four weeks (European Parliament and Council of Europe 2003).

Despite the general framework established by the Directive, specific rules on working time may vary depending on the laws of the Member State. The choice of countries for a more detailed analysis in this study is based on their different roles and patterns in the context of cross-border labor mobility within the European Union. The focus on specific countries reflects their role as major destinations for cross-border workers. These countries have significant economic pull factors, such as higher wages or demand for skilled labor. Let us consider some of them:

1) Germany: The Working Time Act 1994 stipulates that a standard working day should not exceed 8 hours. However, provided that the average working day within six months or 24 weeks does not exceed 8 hours, it is possible to work up to 10 hours per day (Arbeitszeitgesetz 1994).
2) France: the standard working week is 35 hours. This issue is regulated by the Labor Code (Code du travail 1910). Any work beyond this limit is considered overtime and must be paid accordingly (Oqunsanya 2023). The legislation also provides for additional breaks and reduced working hours for certain categories of workers, such as young workers (Troadec 2022).
3) Italy: according to Legislative Decree No. 66/2003 (Decreto Legislativo 2003), in Italy, the working week is usually 40 hours and the maximum working hours per week should not exceed 48 hours, including overtime. Overtime is also limited and must be paid at higher rates.
4) Spain: The standard working week in Spain is 40 hours according to the Workers' Statute. The legislation provides for a 12-hour rest period between working days and mandatory breaks for employees if the working day exceeds 6 hours (Real Decreto Legislativo 2/2015; Estatuto de los Trabajadores 2024).
5) Sweden: The Working Time Act stipulates that in Sweden, the working week is usually 40 hours according to the Working Time Act, but national collective bargaining agreements may provide for fewer hours or additional holidays. The maximum working week, including overtime, should not exceed 48 hours (Arbetstidslagen 1982).
6) The Netherlands: the working week should generally not exceed 40 hours according to the Working Time Act. The law also regulates flexible working hours and remote work (Arbeidstijdenwet 2022).
7) Denmark: The Employer-Employee Relations Act establishes a standard working week of 37 hours. The law regulates working time issues, including flexible working hours and vacation (Arbejdsgiverens pligt til at underrette arbejdstageren om vilkårene for ansættelsesforholdet 2002).
8) Finland: the standard working week in this country is 40 hours according to the Working Time Act. The law also provides for flexible working hours and remote work (Työaikalaki 2019).

The legislation of the European Union establishes general principles and minimum standards regarding working hours that must be adhered to by all Member States. These standards, particularly Directive 2003/88/EC (European Parliament and Council of Europe 2003), guarantee a basic level of protection for workers' rights, including limitations on the maximum duration of the workweek, minimum rest periods, and paid leave. This creates a unified legal framework that promotes the harmonization of working conditions within the EU, ensuring equal conditions for all workers regardless of their country of employment.

At the same time, EU legislation allows Member States some flexibility in defining more detailed provisions regarding working hours, enabling them to take into account national specificities and labor market needs. In some countries, stricter norms than those set by European standards are established, aimed at providing additional protection for workers' rights (Tkachenko 2024a). For example, in France, the standard workweek is reduced to 35 hours, which represents a more progressive approach to protecting the balance between work and personal life. Such national initiatives demonstrate the Member States' commitment to improving labor standards in their respective markets.

This flexibility allows Member States to adapt general European norms to their own realities while ensuring that the minimum standards set by the EU are not violated. This contributes to the development of a single labor market in the EU, where workers' rights are protected at a high level, regardless of their place of employment. It is important to note that while Member States can establish stricter rules, they must do so in a way that does not create unjustified barriers to economic activity or violate the fundamental freedoms of the EU.

Thus, national laws on working hours in EU Member States not only complement the overall European norms but also enhance the level of worker protection by adapting rules to local conditions. This allows for the creation of more favorable conditions for workers while also supporting economic stability and competition in the European labor market. In the next section, we will examine how these legal frameworks and national specificities affect cross-border worker mobility, particularly in the context of different time zones and work cultures.

It is worth noting that the study of the impact of working time on employee mobility cannot be complete without analyzing flexible working hours and regulations governing remote work. They have become important elements of the modern labor market in the European Union, especially in the context of rapid technological change and the COVID-19 pandemic. These forms of work organization allow employees to better balance their professional responsibilities with their personal lives, increase productivity and job satisfaction, and help attract and retain qualified personnel. At the same time, EU member states have different approaches to regulating and implementing flexible work arrangements and remote work, taking into account national peculiarities and labor market needs. Telework offers a solution to social challenges related to transportation and the environment, while also providing individuals with greater flexibility to organize their personal and professional lives. It enhances opportunities for learning and education, fosters independence, and boosts creativity, enabling employees to make meaningful contributions to their organizations (Wojčák and Baráth 2017).

In the Netherlands, for example, flexible working hours and remote work are well integrated into labor law. The Flexible Work Act (Wet Flexibel Werken 2022) allows employees to submit formal requests to change their work schedule, workplace, or number of working hours. Employers are obliged to consider such requests and provide reasonable responses. This approach helps to ensure that flexible working becomes the standard rather than the exception, providing employees with the opportunity to customize their work to meet their personal needs (Fiontar 2021).

Sweden is also one of the leaders in the implementation of flexible working hours and remote work. Swedish labor law provides employees with considerable freedom in choosing their working hours, especially for parents with young children. The Working Time Act (Arbetstidslagen 1982) stipulates that employees can negotiate flexible working arrangements with employers, including the possibility of remote work (Government Communication 2020). This practice is widely supported by employers, as it contributes to increased employee satisfaction and loyalty to the company.

In Italy, the Law on Flexible Work, also known as "smart work", was adopted in 2017. It allows employees to negotiate flexible working hours and the possibility of remote work with their employers. Italian law provides for considerable freedom in determining working conditions, allowing employees to work from home or any other location without a fixed workplace, thus increasing efficiency and job satisfaction (Tutela del Lavoro Autonomo e Lavoro Agile 2017).

In France, flexible work arrangements and remote work are also actively developing. The law on remote work, which was adopted in 2017, simplified the procedure for implementing remote work by allowing employers and employees to agree on such conditions without the need to amend employment contracts (Loi Travail 2017). France has also introduced the concept of the "right to disconnect" (droit à la déconnexion), which obliges companies to define periods when employees have the right not to respond to work-related messages, which is an important element in ensuring work-life balance (Sampaio 2022).

Spain is actively adapting its labor legislation to the new realities of the labor market. The Teleworking Law, adopted in 2020, establishes the rights and obligations of employees and employers in the field of teleworking, including compensation for equipment and other work-related expenses. The law also defines the right of employees to a flexible work schedule, allowing them to organize their work in a way that meets their personal and family needs (Ley 10/2021).

From a broader perspective, these examples demonstrate that certain EU countries (such as the Netherlands, Sweden, Italy, France, and Spain) are actively developing legal frameworks for flexible and remote work. Such actions create significant opportunities for cross-border workers. Legislation in these countries often provides clear guidelines and encourages employers to implement flexible work arrangements. This reduces administrative barriers and facilitates cooperation between companies and professionals from different countries. Ultimately, this reduces obstacles to cross-border employment. At the same time, there are still EU countries where such innovations are still at an early stage or are not sufficiently detailed in legislation. For employees working abroad, this may mean additional problems. For example, the lack of clear rules on remote work expenses, obstacles in negotiating flexible working hours, etc.

Flexible working hours and remote work have become essential elements of labor relations in EU Member States, contributing to the creation of a more adaptable and balanced work environment. Despite the common European framework, each country develops its own approaches to regulating these forms of work, taking into account national traditions and labor market needs. This allows for additional protection and flexibility for employees, which is necessary for successfully adapting to changes in the modern world of work. In the next section, we will examine the

impact of different work cultures and time zones on cross-border worker mobility within the EU, as well as how flexible working arrangements may facilitate or complicate this process.

The differences in approaches to organizing working hours and implementing flexible work schedules and remote work across various EU Member States have a significant impact on cross-border worker mobility. On one hand, the diversity of national regulatory models can create barriers to mobility, as workers may face challenges adapting to new working conditions. For example, a worker from a country with strict control over working hours and limited flexibility might struggle when transitioning to work in a state where such practices are more widespread and expected.

On the other hand, flexible work schedules and the possibility of remote work can greatly enhance cross-border mobility by giving workers more freedom in choosing their work location and organizing their work hours. This is particularly relevant for highly skilled workers, who often have the option to work from anywhere in Europe, without being confined to a physical workplace. In such circumstances, mobility becomes not just a matter of relocating between countries but also a way to maintain employment in international companies while working from different locations. In conclusion, while differences in the organization of working hours can present challenges for cross-border mobility, they also open up new opportunities for both workers and employers. Flexibility in approaches to work organization can facilitate a more effective adaptation to different working conditions, which is a key factor in the successful integration of workers into new working environments within the European Union.

4.3 The impact of different time zones on the workflow

The European Union covers three main time zones (Tab. 2). At first glance, these differences may seem insignificant. Especially when compared to the fluctuations of global time zones. Nevertheless, they still pose problems for cross-border labor mobility and international cooperation.

So, for example, an employee in Portugal (GMT) collaborating with a company in Germany (CET, UTC+1) or Greece (EET, UTC+2) may need to adjust their working hours to match those of their colleagues or clients. Knowledge-intensive industries such as IT, finance, and consulting rely heavily on real-time collaboration. A one- or two-hour time gap can delay decision-making, requiring companies to adopt asynchronous communication strategies. Employees may have problems with irregular working hours. This leads to stress and disruption in their personal lives.

The impact of different time zones on the work process is a crucial factor to consider in the context of cross-border worker mobility and international collaboration (Tang et al. 2011). Watson-Manheim, Chudoba, and Crowston (2012) suggest that these inconsistencies might arise because researchers have not adequately distinguished between the boundaries themselves and the effects they produce when crossed. Organizational discontinuity theory conceptualizes these boundary-crossing effects as "discontinuities" and "continuities". Discontinuities occur at a boundary when information and communication flows demand conscious effort and attention to manage, while continuities exist when these flows occur as expected, requiring minimal coordination across boundaries. Although boundaries may appear similar across different contexts it is through the presence of discontinuities and continuities that they exert different impacts on collaboration. This framework is valuable for understanding the varied experiences of global virtual workers as they collaborate across boundaries (Sivunen et al. 2016). Firstly, different time zones can complicate coordination between employees working in different countries.

The added value in cross-border labor mobility, along with the economic development of participating countries, is further influenced by the ability to manage time zone differences effectively. Due to the diverse nature of labor sectors, findings highlight the importance of considering the impact of time zones on various industries. Managing time zone challenges is especially critical for knowledge-intensive sectors, such as professional, scientific, technical, and information services, where seamless communication and coordination are vital (Christen 2012).

Secondly, different time zones can affect the efficiency of communication with clients and partners, particularly if they are located in different countries. For example, clients in one time zone may require an immediate response when the workday has already ended in another country. This can lead to delays in response and a reduction in the level of customer service. Building continuities across temporal boundaries in global work was also linked to how informants managed their personal work-life boundaries. Specifically, the need for constant availability through various communication channels in global work posed

Tab. 2 The distribution of time zones in the EU countries.

Member State	Time Zone
Ireland, Portugal	GMT (UTC+0)
Austria, Belgium, Croatia, Czech Republic, Denmark, France, Germany, Hungary, Italy, Luxembourg, Malta, Netherlands, Poland, Slovakia, Slovenia, Spain, Sweden	CET (UTC+1)
Bulgaria, Cyprus, Estonia, Finland, Greece, Latvia, Lithuania Romania	EET (UTC+2)

a potential discontinuity that collaborators needed to navigate, and they employed different strategies to handle this challenge (Sivunen et al. 2016). On the other hand, time zone differences can be advantageous if the work process is properly organized (Prychepa et al. 2018). For example, companies can use time gaps to ensure continuous work processes, where work started in one office can be completed in another, where the workday is just beginning. This can increase overall company productivity by allowing more efficient use of time.

It is also important to consider the impact of time zones on the health and well-being of employees (Myronchuk 2020). Prolonged work in conditions requiring adaptation to different time zones can lead to stress and disrupt the balance between work and personal life. Therefore, companies should develop strategies that help employees effectively manage these challenges by providing flexibility in work schedules and supporting a healthy work environment. In conclusion, the impact of different time zones on the work process can be both a challenge and an opportunity. Success depends on how well an organization can adapt its processes to these conditions, ensuring effective communication, coordination, and support for its employees in an international context.

4.4 Work cultures in different EU Member States and their impact on mobility

The importance of corporate culture in creating organizational unity, shaping employee behavior, and driving strategic goals is immense. It encompasses the shared values, beliefs, and practices that define an organization, impacting both internal operations and external relations. Schein's foundational work on organizational culture provides a framework for understanding its layers, including artifacts, espoused values, and underlying assumptions, all of which collectively influence organizational behavior (Schein 1985).

However, corporate culture is far from uniform; it varies greatly across different cultural contexts. National culture, shaped by historical, social, and institutional factors, plays a significant role in influencing organizational practices and behaviors. Geert Hofstede's cultural dimensions' theory highlights key dimensions such as power distance, individualism versus collectivism, uncertainty avoidance, and masculinity versus femininity, offering valuable insights into the cultural differences that exist among nations (Hofstede 1980; Cîmpeanu and Pîrju 2010; Nakonechna 2024). Work cultures in the EU are multifaceted and reflect the national traditions, historical development and social norms of each country. They include different approaches to working hours, hierarchical structures, work-life balance, and ways of communicating and making decisions (Steindl and Jonas 2012).

For example, in the Nordic EU countries, such as Sweden and Denmark, the work culture emphasizes the importance of work-life balance (Hofstede et al. 2010). Flexible working hours, the ability to work remotely, and a strong emphasis on collective decision-making prevail here. In contrast, in southern countries, such as Italy and Spain, work cultures are often characterized by more traditional approaches with a clear hierarchical division of responsibilities and a strong emphasis on personal relationships in the professional environment (Nakonechna 2024). In Germany and Austria, the work culture is highly structured and punctual, with working hours being a priority. In contrast, France often has a more flexible approach to working hours, albeit with an emphasis on protecting employee rights (Wojčák and Baráth 2017; Nakonechna 2024).

These differences affect the cross-border mobility of employees in the EU, as they have to adapt to new work environments, understand and take into account the cultural characteristics of the country to which they move (Casis 2022; Yaroshenko et al. 2024). Adapting to new working conditions is one of the key challenges to cross-border mobility within the EU. When employees move to another country, they face not only a new cultural environment but also different standards, practices, and workplace expectations. These changes can significantly impact their ability to effectively integrate into a new team and perform their professional duties.

One of the most challenging aspects of adaptation is understanding and embracing new workplace cultures, which can differ greatly from what the employee is accustomed to in their home country. For example, the level of formality in relationships with management, approaches to conflict resolution, expectations regarding working hours, and the degree of autonomy may vary depending on the country. These differences can be a source of stress and misunderstandings, which, in turn, affect productivity and overall job satisfaction. Furthermore, language barriers can also complicate the adaptation process. Even with a high level of language proficiency, an employee may experience difficulties in communicating with colleagues, especially when dealing with specific professional jargon or cultural idioms. This can lead to feelings of isolation and hinder effective integration into the new work environment.

An important aspect of work culture is the opportunities in the workplace that are related to gender. This has a significant impact on workforce mobility, especially in cultures with a greater emphasis on hierarchical, masculine work environments. Hofstede's Cultural Dimensions Theory identifies masculinity versus femininity as one of the key cultural indicators that shape workplace behavior. In more masculine cultures, such as Germany, Austria, and Italy, the work environment often emphasizes competition, assertiveness, and a performance-oriented attitude. In contrast, more

feminine cultures, such as Sweden, Denmark, and the Netherlands, prioritize work-life balance, collaboration, and employee well-being (Żemojtel-Piotrowska and Piotrowski 2023). For women seeking career opportunities abroad, these cultural differences can be a barrier. They may find it difficult to integrate into a hierarchical, male-dominated environment. This can affect job satisfaction.

Finally, an important aspect of adaptation is the shift in approaches to work-life balance. Different countries have different expectations regarding how much time employees should devote to work and how they can manage their personal lives (Reaney 2012). Facing new norms can be challenging for employees who are accustomed to a different level of flexibility or work intensity. Thus, adapting to new working conditions is a significant challenge that impacts the success of cross-border mobility. It requires employees not only to have professional skills but also to be flexible, culturally sensitive, and capable of quickly learning and adapting (Gallo and Lopez 2023). To facilitate workers' adaptation to the work culture of the country they move to and enhance cross-border mobility within the EU, the following approaches can be proposed.

Establishment of a European orientation and integration program for workers: to develop a unified orientation program covering key aspects of the work culture in each EU member state. This program could include courses, training sessions, and online resources that provide workers with information on local labor standards, employer expectations, cultural nuances, and language differences. This would help reduce cultural shock and ease integration. Existing resources such as EURES (European Employment Services) already provide valuable information, advice, and job-matching services for workers and employers across the EU. EURES covers essential aspects of cross-border employment. However, while these resources are extensive, several gaps remain that limit their effectiveness in fully supporting workers' integration into new work cultures. A critical analysis of EURES and similar platforms highlights several areas for improvement. First of all, there is limited attention to cultural adaptation in the workplace. EURES provides general information on living conditions and labour market rules. However, it lacks practical guidance on workplace norms and expectations in different EU countries. Additional resources should include interactive training on workplace etiquette to help employees adapt to the new corporate culture.

Furthermore, there is a lack of personalised support for integration. The platform mainly provides generalised information. Introducing individual counselling services could significantly improve its effectiveness. Although EURES provides job matching services, it does not offer comprehensive digital training to prepare workers for the modern demands of the labour market. Therefore, it seems appropriate to expand the platform with digital training modules from professional networks.

Therefore, instead of developing a completely new integration programme, improving EURES would be a more effective solution. This approach ensures that employees gain practical knowledge about adapting to different work cultures.

1) Support for mentorship and partnership programs: implement a mentorship system where experienced workers or managers who have already successfully adapted to local conditions assist newly arrived workers. These mentors can help with practical issues and provide recommendations on effectively interacting in the new work environment.
2) Harmonization of minimum labor standards: the EU could develop guidelines to harmonize certain aspects of work culture, such as standard procedures for conflict resolution, expectations regarding working hours, formality in relationships with management, and approaches to ensuring work-life balance. While full unification is impossible due to national differences, establishing minimum standards would help reduce cultural barriers.
3) Expansion of language courses and cultural training: fund and support language courses and cultural training programs available to workers planning to move or who have already moved to another EU member state. This would not only improve language skills but also deepen understanding of the local culture and business etiquette.

In our opinion, these approaches would help create more favorable conditions for workers, increase cross-border mobility within the EU, ease the process of adapting to new working conditions, and promote more effective integration into the new work environment.

5. Discussion

The cross-border mobility of workers in the European Union is one of the most striking examples of integration in the context of globalization. However, despite the obvious benefits, such as access to a wider labor market, improved professional skills, and personal development, this process faces a number of profound challenges (Rym 2019). These challenges go far beyond legal and administrative obstacles, affecting the very nature of human labor, personal identity, and cultural interaction.

One of the newly analyzed issues identified in this study is the impact of different national approaches to social security systems and working conditions. This gap exacerbates the difficulties of ensuring smooth mobility of workers. While the issue of work has been extensively studied, this research highlights a critical gap: the challenges associated with coordinating

across time zones and reconciling work schedules in a way that respects both individual needs and organizational efficiency. The findings suggest that this problem has been exacerbated by the emergence of work environments. They require new approaches to regulation. Another new aspect that is being analyzed is the role of cultural adaptation in mitigating cross-border conflicts. This is especially true in environments where workplace norms are in significant conflict with employees' personal values. For example, this study provides new insights into how collectivist-oriented employees face unique challenges when integrating into individualistic workplace cultures. Such challenges require not only professional adaptation, but also profound personal transformations (Nakonechna 2024).

Another important challenge is the issue of time and space. In the era of digital technologies and global markets, employees often face the need to work in different time zones, which can lead to disruption of their personal lives and exacerbate the problem of work-life balance (Barada 2013). The issue of working time is of particular importance, as each country has its own approaches to its regulation (Sivunen et al. 2016; Tkachenko 2024b). Discrepancies in the established working hours can create additional difficulties in organizing joint work and effective communication between employees from different countries (Tang et al. 2011). In addition, cross-border mobility forces us to rethink questions of identity and belonging (Hofstede 1980; Cîmpeanu and Pîrju 2010; Nakonechna 2024). In today's world, where people are increasingly moving around in search of better opportunities, the question arises: can we maintain our cultural and national identity while integrating into new social and professional environments? This process is often accompanied by an internal conflict between the desire to preserve our uniqueness and the need to adapt to new conditions, which can cause feelings of loss or dispersion.

Finally, global mobility challenges the very notion of community (Recchi 2014). Traditionally, communities were formed around shared values, customs and territory (Fernández et al. 2016; Mazzoni 2017). However, when workers are constantly on the move, the question arises: how can we maintain connection and community in such a dynamic and changing world? This requires not only new approaches to work organization, but also a new understanding of what it means to be part of a community on a global scale. Therefore, the challenges of cross-border mobility in the EU go beyond purely economic and administrative aspects. They force us to think about deeper questions concerning our identity, values, time and space, and the very meaning of community in the modern world (Mazzoni 2017). Addressing these issues requires not only legislative changes, but also a philosophical understanding of the new reality in which we live.

The study highlights several key findings:

1) Legislative disparities, such as differences in working hours and social security systems, remain significant obstacles to mobility.
2) Cultural adaptation, including language skills and knowledge of workplace norms, is crucial for effective integration.
3) Flexible working arrangements, including teleworking, present both opportunities and challenges, especially with regard to coordination across time zones.

A comparison with existing research supports these findings. For example, Barslund and Busse (2016) have highlighted the need for legislative harmonisation to optimise labour market efficiency, in line with the findings of this study. Similarly, Nakonechna (2024) has highlighted the importance of cultural adaptation, which echoes the focus of this study on the role of cultural differences in mobility. Furthermore, recent work by Bruurs (2023) on teleworking highlights the need for a clear regulatory framework, especially in an environment where teleworking is becoming increasingly popular.

Thus, the conducted research has demonstrated the key challenges regarding worker mobility. At the same time, the prospects for cross-border mobility are obvious. Based on the conducted analysis, we can propose a number of improvements. The differences identified in working hours and social security coordination indicate the need to unify the EU directive (Malynovska 2021; Getman et al. 2023). This will help to reduce gaps in living standards and working conditions between different countries. In turn it will stimulate the mobility of workers who will be more confident in their rights and social protection regardless of the country of work. Establishing minimum standards helps to reduce regulatory gaps. In addition, the development of technology and the introduction of digital platforms can greatly simplify the employment and adaptation of workers in new countries. For example, the creation of single online platforms for finding jobs that match a worker's qualifications, integrated with systems for recognizing diplomas and certificates, can greatly facilitate the employment and transition processes between countries.

Investments in language training and cultural adaptation are also important opportunities to improve mobility. Providing access to free language courses and cultural adaptation programs will help employees integrate into their new work environment faster, reduce communication barriers, and increase their effectiveness in the new environment. It is also worth considering the creation of intergovernmental employee exchange programs that would allow people to gain experience in different EU countries. Such programs will not only help improve professional skills, but will also help to form a common European work culture, which will be a powerful tool for further development of the common market.

The third recommendation is to ensure fair working conditions. The data on teleworking underlines the need to create pan-European standards that balance the needs of employees and employers.

This research contributes to both academic literature and policy-making by providing new perspectives on the barriers and opportunities in cross-border mobility. By addressing underexplored aspects, this article establishes a foundation for developing practical solutions. These findings highlight the need for comprehensive and coordinated actions to transform cross-border mobility into a more equitable and efficient process, ultimately strengthening the EU's labor market integration.

6. Conclusion

Cross-border labor mobility within the EU is a complex and multifaceted phenomenon that requires a deep understanding of economic and legal frameworks as well as cultural and social factors. European legislation, particularly the legal acts analyzed in this article, provides the basic principles and rules that help create conditions for the free movement of labor. However, this process is not limited to the legislative framework; it also involves the active adaptation of workers to new working environments and cultures, which, in turn, requires flexible approaches and an understanding of diversity.

The flexibility of working conditions, particularly remote work and flexible schedules, significantly simplifies the process of workers adapting to new labor conditions in different countries. At the same time, they present new challenges for employers, who must ensure effective coordination and management of work processes, especially in cases of differences in time zones and cultural distinctions. This necessitates the development of new management strategies aimed at reducing the impact of these factors and increasing labor productivity.

Cultural differences among EU member states can both facilitate and complicate the process of integrating workers into a new environment. Organizational culture, reflected in the values, traditions, and practices of different countries, influences how workers perceive their role in a new team and how they adapt to the employer's demands. The role of national governments and social partners in facilitating successful worker adaptation through training programs and social support is also crucial.

Moreover, the development of European institutions aimed at harmonizing labor laws, particularly concerning the protection of workers' rights and ensuring equal opportunities, is critical for further strengthening the single market. Harmonization of legal norms helps eliminate barriers to mobility and provides a more predictable and stable environment for workers and employers alike.

In light of current challenges such as digitalization, changes in work organization, and globalization, the EU must continue to improve its legislation and support mechanisms for mobility. This will not only promote economic development but also ensure social stability and cohesion within European society. Ultimately, the success of European integration depends on the ability of member states to cooperate and find common solutions to shared problems, as well as on the willingness of workers to adapt to the new realities of the labor market.

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Layout structure of rural settlements and adjacent new developments in Czechia: Classification system and implications for urban planning

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ABSTRACT
In this article a spatially integrative classification system of rural settlements based on their historical layout structure is proposed and applied to all eligible rural settlements in Czechia. This classification is then used to assess spatial characteristics of recent suburban developments, including the structure of their street networks and their spatial relationship to historical cores. Based on orthophotomaps, historical maps, and old classifications from the last century, a six-type classification system was created and applied to all rural settlements with less than 3,000 inhabitants in Czechia. In addition, based on a randomly selected subsample of 60 suburbanized settlements, the street network layout of the new developments (geometrical/organic/combined) was identified, and the adjacency of the new and old developments analyzed. The village-square type was the most common historical layout (52%), followed by stripe-type (26%), small (8%), plot-type (4%), and dispersed types (2%). All the remaining layout structures, aggregated into the Others category, represented 8% of settlements. New developments in the two predominant types of historical layouts are mostly geometric and, with a few exceptions, adjacent to the original settlement core. The developed classification system can serve as a basis for a discussion about suitable and sensitive planning of new developments that preserve the historical value of the original settlements while supporting their sustainable growth.

KEYWORDS
rural settlements; historical layout; settlement structure; suburbanization; street network; rural landscape; conservation, Czechia

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1. Introduction

Rural settlements have an irreplaceable position in the landscape. In Central Europe, most of them acquired their basic form in the 11th–14th century and give witness to their continuous development in relation to the farmland and surrounding landscape. Agriculture and the relationship of settlement inhabitants to the surrounding landscape significantly influenced the settlement layouts and their structure (Perlín et al., 2010). In Eastern and Central Europe, the relationship of rural settlements to the landscape experienced major changes during the Industrial Revolution and (particularly) the second half of the 20th century, when collectivization and formation of agricultural cooperatives led to major changes in the landscape and settlement structure (Bičík 2002; Bičík et al. 2001; Hanušin et al. 2020; Kupková et al. 2021). Scholars like Iordachi (2013) have explored similar transformations in rural landscapes across Europe, highlighting the widespread impact of industrialization and collectivization on settlement patterns.

With the turn of the millennium, the rural landscape, especially that in the background of major cities, was challenged with a new trend – massive suburbanization (Baše 2004; Ouředníček 2003; Sádlo 2008). This phenomenon has been extensively studied internationally, emphasizing the socio-economic and environmental consequences of suburban sprawl (Hirt 2012; Moudon and Hess 2000; Scheer 2019). In many cases, an insensitive approach to the new developments – from the urban planning as well as architectural perspectives (Hanušin et al. 2020) – began to massively disturb the original character of rural settlements (Roberts 1997; J. Roberts and Wrathmell 2003; J. Sýkora 1998). Interactions of the original and new settlement structures from both the cultural and social perspectives have been the subject of many studies (Ouředníček 2007, 2015; L. Sýkora 2009; L. Sýkora and Mulíček 2014).

To fully appreciate the dynamics of rural settlement development and preservation, it is crucial to incorporate a comprehensive theoretical background. The importance of rural settlements extends beyond the local context (Fanta et al. 2022), reflecting broader geographical, social, and environmental interactions that are globally relevant. For instance, Smardon (2022) and Tress et al. (2005) highlight the multifaceted role of landscapes in rural areas, emphasizing their ecological, cultural, and socio-economic dimensions. Similarly, Antrop (2005) discusses how landscape changes in Europe are driven by a complex interplay of historical, economic, and policy factors. Scholars like Pedroli et al. (2007) argue for integrated landscape approaches that balance conservation with sustainable development, ensuring that rural settlements can evolve without losing their distinctive character.

The typology of settlement structures in old villages is a crucial aspect of studying the historical development of rural areas (Kadlec et al. 1961; Láznička 1946, 1956; Máčel 1955; Máčel and Viklický 1954; Pešta 2000; Roberts and Wrathmell 2003; Škabrada 2022; Škabrada and Voděra 1975; Viklický 1953). Settlements in various geographical and cultural contexts exhibit specific features closely linked to the landscape and its resources. In Europe, several basic typologies can be identified, including street villages, village-square settlements, dispersed settlements, and planned settlements that emerged during periods of colonization or industrialization.

One of the most common types is the street village, characterized by a linear arrangement of houses along a main road. This typology often reflects the historical importance of transportation routes and accessibility to resources (Thompson et al. 2020). The linear pattern facilitated efficient communication and transport, crucial for agricultural societies (Fanta et al. 2022; Houfková et al. 2015). The regularity of street villages indicates a planned approach to settlement, often seen in regions with a long history of centralized governance (Whitehand and Morton 2004).

Another prevalent type is the village-square settlement, where houses are arranged around a central open space or square. This layout is particularly common in Central and Eastern Europe and often indicates a communal approach to village life, with the square serving as a focal point for social, economic, and administrative activities. The central square typically housed important community structures such as churches, markets, and meeting halls, reinforcing its role as the village nucleus (Kuča 2013).

Dispersed settlements represent a different typology, where houses and farms are spread out over a large area rather than concentrated along a road or around a square. This pattern is often found in regions with abundant arable land, where agriculture dictates a more spread-out settlement to maximize land use. Such settlements can be indicative of historical land ownership patterns and agricultural practices that required proximity to the fields (Pedroli et al. 2007).

Planned settlements, which emerged during colonization periods or industrialization, often exhibit a grid pattern (Škabrada 2022). These settlements were systematically designed to optimize land use, infrastructure, and accessibility. The grid pattern, commonly associated with Roman urban planning, was later adopted during various periods of territorial expansion and economic development in Europe. This type reflects a high degree of planning and control, often linked to state-driven colonization efforts or company towns established during the industrial era.

The context of the valuable original character of rural settlements is, unfortunately, often neglected. While some highly valuable settlements are protected as heritage, this is not true of the majority of rural

settlements throughout not only the Czechia but entire Europe. It is, of course, impossible to conserve the status quo in such settlements – the pressure on new developments is immense and the settlements generally tend to grow. Land use planners are, however, often faced with the dilemma of whether new developments should be constructed adjacent to the original village core or if they should be rather created in completely new areas separated from the original valuable core. Taking into account the original settlement layout and structure could help in this decision-making.

The original layout type generally does not draw sufficient attention from land use planners. Many works have focused on the structure from the perspective of transportation infrastructure (Gil et al. 2012; Huang et al. 2007; Southworth 1997; Wheeler 2015; Whitehand and Morton 2004). However, the layout of the core parts, which, besides reflecting the historical development of the settlement over time as mentioned above, can be also characteristic of certain regions and/or contains valuable ecological structures, is only rarely studied (Hanušin et al. 2020; Kuča 2009, 2013; Pešta 2000; Roberts 1997; Škabrada 2022). In the Czechia, this has been the subject of studies during the second half of the last century (Kadlec et al. 1961; Láznička 1956; Máčel 1955; Máčel and Viklický 1954), when several relatively complicated classification systems were developed. Since then, this topic has, unfortunately, been neglected, although a few studies in Czech journals have been published by Pešta (2000), Škabrada (2022) or Kuča (2013), whose classification system distinguished 22 types of rural settlements. That system is, however, quite complicated from the perspective of its applicability in large areas or automation using artificial intelligence (AI) techniques. International perspectives, such as those provided by Evert Meijering et al. (2007), who discuss the complexities of rural transformation in different European contexts, can offer valuable insights into how rural settlements can be classified and managed.

The influence of suburbanization on rural areas in Czechia became particularly pronounced in the 1990s and 2000s, especially in the suburban zones of large urban agglomerations (Ouředníček 2003; L. Sýkora 2003). The rapid growth of new residential developments at the edge of traditional villages during this period often undermined historically evolved spatial structures (Baše 2002b, 2004; Maňas and Kabrhel 2024; Šťastná et al. 2015, 2018) and disrupted the cultural landscape. While typological knowledge of rural settlements is essential for understanding the foundation upon which these transformations occur, it is equally important to analyze how suburbanization interacts with these existing forms (Baše 2001, 2006; Cílek and Baše 2005). In this context, the classification system presented in this paper is not an end in itself but a tool for assessing and guiding new developments in a way that respects the inherited structure and identity of rural settlements.

In this paper, therefore, we aim to: (a) formulate a new simple, yet effective, system of rural settlement classification based on the previously published typologies, (b) evaluate the representation of individual layout types in rural settlements in the Czechia and discuss the regional variability in the representation of individual types. Further, on an example of 60 rapidly developing rural settlements that have, until recently, maintained their original layout, to (c) investigate the types of new developments (geometrical vs organic) and to compare the representation of these two types from the perspective of the original layout type. In addition, (d) the adjacency of the new developments to the original settlements was analyzed. Finally, (e) based on these results, contribute to the discussion about the impacts of suburbanization on rural settlement integrity and outline directions for more context-sensitive planning strategies.

This study addresses two critical research questions regarding rural settlements. (1) How do new developments in rural settlements differ in their street network structure compared to the original settlement cores? And (2) what is the spatial relationship between new developments and original settlement cores in rapidly suburbanizing rural areas?

To correspond with objectives (a) and (b), two additional questions are formulated: (3) How is the current regional distribution of rural settlement layout types in Czechia structured? (4) To what extent can the morphological characteristics of rural settlements be differentiated using the proposed simplified classification system?

2. Methods

2.1 Classification system

In the first step, we developed a new system of settlement layout classification based on the classification systems published previously (Kuča 2009; Máčel 1955; Máčel and Viklický 1954; Pešta 2000; Škabrada 2022). As these classification systems were useful but, at the same time, probably unnecessarily complicated for the intended analyses (Tab. 1), the new system was to a large degree simplified, containing only 6 basic types of settlement core layout structures (Fig 1): **Village-square type** (or square-type, Fig. 1a) is characterized by a village square, which used to form the center of the settlement. Entrances to individual farmsteads open into the square, backyards then continue into fields. Typically, these settlements were originally linked with the surrounding settlements by just one or two roads and their layout was typically circular or ellipsoid. **Stripe-type** settlements are characterized by a central road and individual buildings open into the road (Thompson et

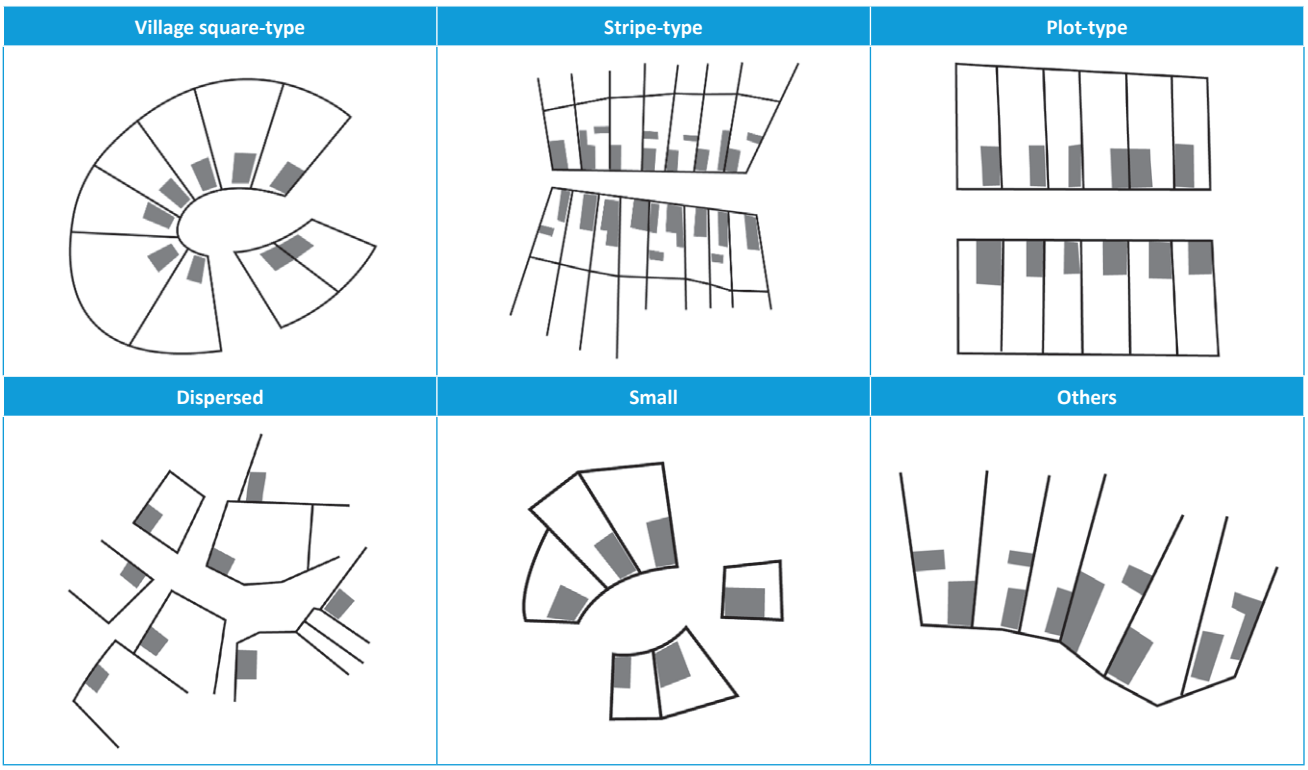

Fig. 1 Basic layout-based typology of the cores of rural settlements.

Tab. 1 Classification systems for rural settlements in the region of the Czechia reported in the literature previously.

Author	(Máčel 1955)	(Černý 1979)	(Frolec and Vařeka 1983)	(Kuča 2013)
Number of types	24	9	7	22

al. 2020). This also determines the long and narrow shape of the settlement. **Plot-type** settlements are similar to the stripe-type ones, the main difference lies in more precise determination of individual plots, often of equal sizes. This is caused by the fact that this type of settlement is much younger than the previous ones – only approx. 200 years. **Dispersed-type** settlements are typical of submontane and montane regions where the landscape morphology does not support a compact layout. **Small-type** settlements can vary in shape but they are generally so small that they cannot be clearly defined to belong to one of the fully developed morphologies described above. Lastly, the class **Others** aggregates types that are not small but do not fit any of the above-described morphologies – for example, settlements situated only along one side of a road or with unclear shapes.

This new classification was derived through comparative visual analysis of previous typologies. The six types were selected to simplify redundant distinctions and emphasize basic spatial features relevant for further analysis. Prior typologies were compared side-by-side and interpreted using orthophoto and cadastral maps. Subsequently, this typology was used to classify approximately 5,000 rural settlements in the Czechia.

It should be noted that some categories (particularly the stripe-type) include morphologically similar settlement forms that, however, originated under different historical and colonization conditions (e.g., organically developed street villages in southern Moravia vs. planned Waldhufendörfer in northern Bohemia). The present classification groups them based on layout characteristics relevant for spatial analysis, but these internal historical distinctions may be important for deeper landscape or cultural studies.

2.2 Study area and data

In this paper, we used data describing the Czechia (Central Europe). For the classification of the entire area of the Czechia, we employed cadastral maps and orthophoto maps available from the State Administration of Land Surveying and Cadastre, along with the original classifications of settlements from previous works (Kadlec 1961; Kadlec et al. 1961; Kadlec and Smržová 1970; Kuča 2009, 2013; Láznička 1956; Máčel 1955; Máčel and Viklický 1954; Pešta 2000; Škabrada 2022). Based on these data, all village-type settlements (i.e., those with populations of less than 3,000) in the Czechia were classified using the above-described classification system.

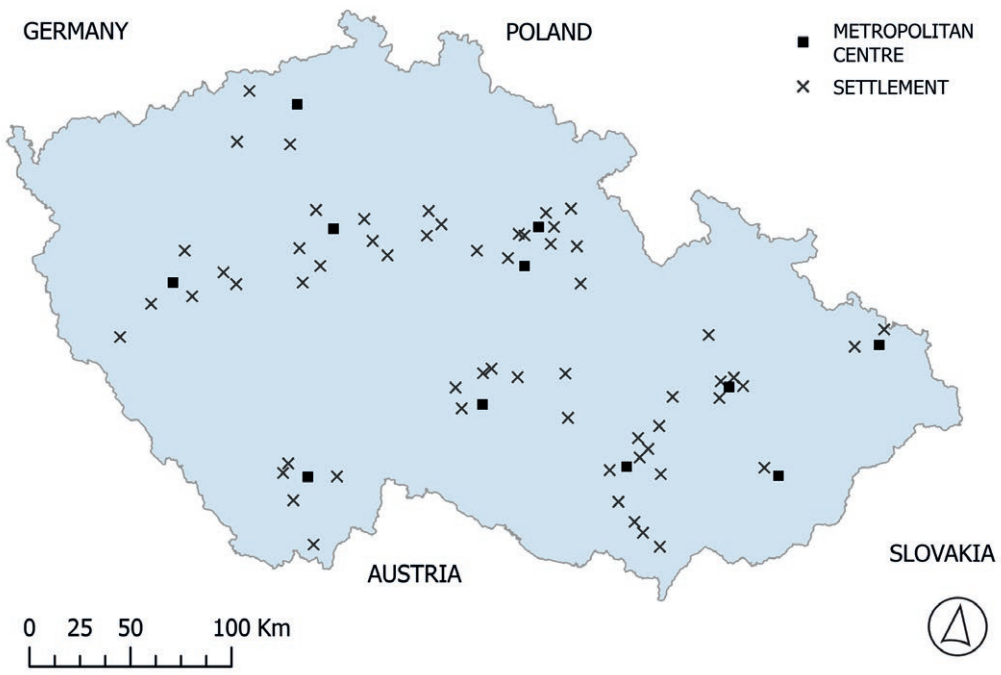

Fig. 2 The location of analyzed rapidly developing rural settlements within the Czechia.

Altogether, approximately 5,000 rural settlements meeting the defined population and spatial criteria were included in the classification.

The classification was performed manually through visual interpretation of orthophoto and cadastral maps, focusing on key spatial features such as the structure of the street network, the orientation of built-up plots, and the overall compactness of the settlement form.

In this study, the term settlement refers not to administrative units (such as municipalities or cadastral territories), but rather to a compact built-up structure identifiable in orthophoto and cadastral maps. This includes the core inhabited area of a village or town-like entity, typically excluding scattered farmsteads or isolated housing unless clearly associated with a coherent built-up layout. The spatial boundaries of each settlement were visually interpreted based on the continuity of the urban fabric, building density, and connection via road or infrastructure networks.

Applying the above threshold of a ≥100% increase in housing stock between 2001 and 2021 revealed that roughly every tenth rural settlement – around five hundred of the five thousand classified – can be regarded as rapidly developing. From this subset, 60 settlements distributed across the principal suburbanisation zones of Czechia were then randomly selected for detailed analysis, with the additional requirement that their historic core and the newly built-up areas remained clearly distinguishable in the ortho-photo imagery.

Selection was based on housing statistics and visual assessment of aerial imagery to ensure that both the original structure and new development were clearly distinguishable and suitable for comparative evaluation.

From the preliminary results of the classification of settlements from the entire Czechia performed in the previous paragraph, we knew that village-square-type and stripe-type settlements constituted a vast majority of suburbanized settlements. The plot-type, dispersed, and others were found more frequently in remote regions and not many such settlements were suburbanized. The same is, logically, valid for small settlements – these settlements, remaining small, did not undergo suburbanization. For this reason, we finally analyzed the structure of new developments only in settlements of the village-square-type (30) and stripe-type (30) settlements from suburbanized regions throughout the Czechia.

2.3 Analysis of new developments

As no suitable complex layout-based typology of new developments that would take into account multiple criteria was found in the literature at the time of the analysis, the new developments were classified solely on the basis of the character of the street network into geometric and organic types according to (Kostof 1991). Classification of the new developments according to the street network is common in literature (Frey 1999; Marshall 2004; Rickaby 1987; Satoh 1998) as it is very characteristic of structures formed in the era of individual automobile transport (Marshall 2004; Thompson et al. 2020). In this, the structures of these sites inherently differ from the original (core) historic parts of settlements, which were formed largely in relation to the surrounding (agricultural) landscape.

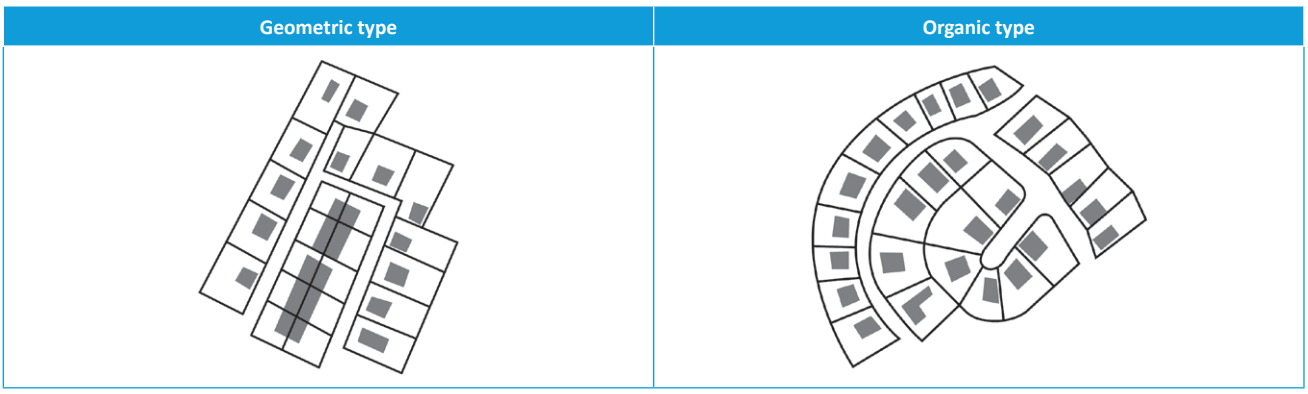

Fig. 3 The basic classification of new developments in the rural settlements according to the street network structure.

Although simple, this approach offers the basic categorization of settlements in various cultures, geographic regions, and time points (Major and Dalton 2018). Where both organic and geometric layouts were present in the particular development, classification was performed based on the predominating layout type (if the representation was >70%, the development was classified as the dominant street network type); where the representation of both types was more balanced (i.e., the predominating type represented less than 70% of the street network), they were classified as the third type – "Combined".

In addition, the interaction between the new and old developments (i.e., whether the new and old developments are connected or separated) was analyzed for each settlement. Old and new developments separated only by a street or with directly adjacent private plots were considered connected.

This assessment was based on visual interpretation of orthophoto maps. Developments were classified as "connected" if the built-up areas were spatially continuous or directly adjacent (e.g., across a road or along shared property boundaries). If the new development was spatially detached, without any direct visual or structural continuity, it was classified as "separated". Consistent criteria were applied across all 60 settlements.

3. Results

3.1 Settlement classification according to the original layout structure

The results of the analysis of the layout of all small settlements in the Czechiaare depicted in Fig. 4.

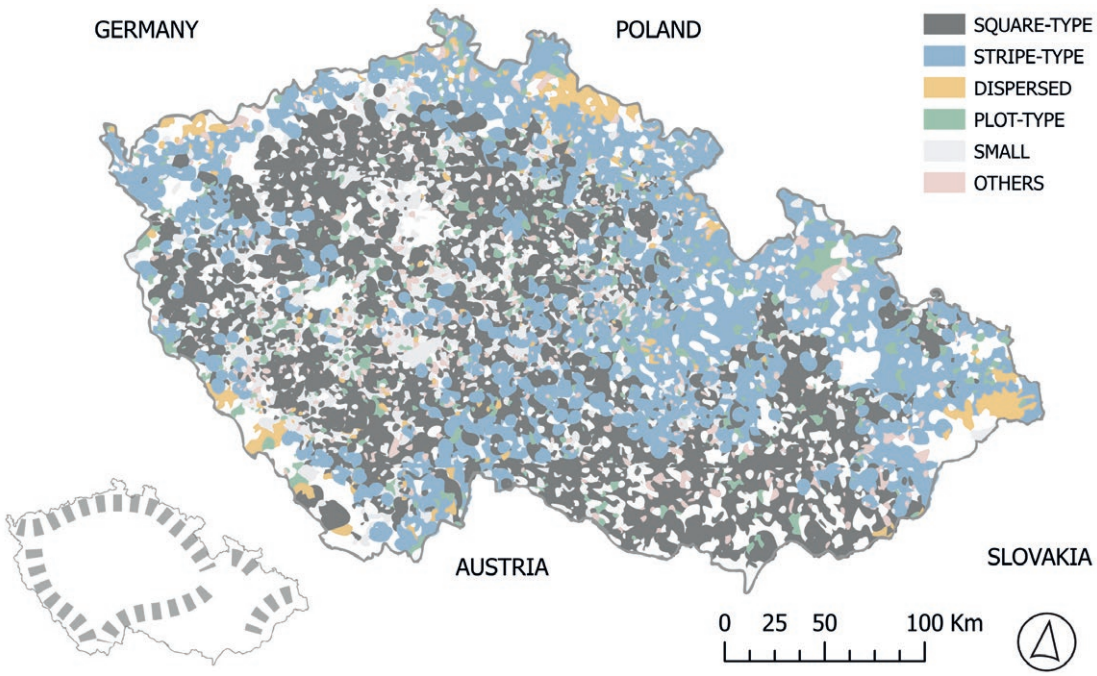

Fig. 4 Main picture: Classification of the rural settlements according to the layout structure of the core (original) parts of the settlements in the Czechia. Small picture: Grey stripes illustrate highland and montane regions.

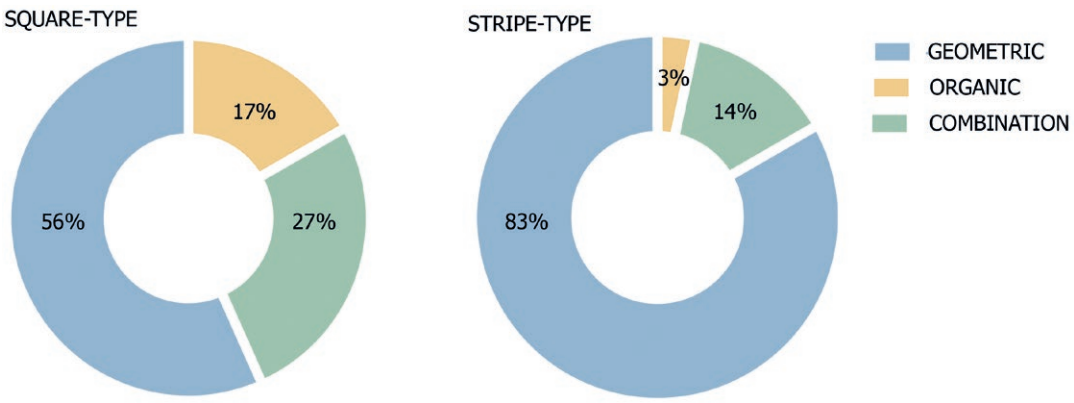

Fig. 5 Classification of new developments according to the street network for village-square type and stripe-type settlements.

Village-square type was the most common, constituting 52% of all settlements. Stripe-type settlements (26%) were the second most common, followed by small (8%), plot-type (4%), and dispersed (2%). All the remaining layout structures, aggregated into the Others category, comprised 8% of settlements. Comparing the distribution of layout types with the morphological map of Czechia (small picture in Fig. 4), we can see that stripe-type settlements are concentrated rather in hilly terrain while on flat terrain, village-square type is dominant. Dispersed settlements are concentrated in mountainous regions, plot-type settlements are relatively evenly distributed throughout the entire territory. Small settlements mostly fill in the gaps among village-square type settlements. Empty (white) spaces in the maps indicate cities, villages with a population of >3000, mining or military areas, and areas near borders where settlements were destroyed or abandoned due to the Iron Curtain.

3.2 Types of new developments

Most rapidly developing rural settlements can be found in the suburban and exurban zones of metropolitan areas, where the demand for housing is high. In this study, the dominant types of such settlements, i.e., the village-square type and the stripe-type, were analyzed further from the perspective of their street network. Purely organic approach to creating new developments was very rare, observed only in 17%

Fig. 6 Examples of new developments unconnected (A) and connected (B) to the original structures. The original cores (square type) are indicated in the pictures. Orthophoto data sourced from the State Administration of Land Surveying and Cadastre 2023.

and 3% of settlements with originally square-type and stripe-type structures, respectively. The geometric street network was clearly predominant in the new developments, dominating in 56% and 83% of settlements with originally square-type and stripe-type structures, respectively. The combined structure was present in 27% and 14% of new developments, respectively (Fig. 5).

3.3 Connection of new developments and the historic cores

In a vast majority of studied settlements, the new developments were connected with the original settlement. The new development remained separated only in four settlements out of the 60 analyzed. Three of those were characterized by the geometric street network, the remaining one was a combined geometric/organic type. The unconnected new developments are characterized by their size – they are always sizeable developments built at one period, in some cases even several times larger than the original settlement.

Where the new developments are connected to the original core structure of the settlement, it is usually at the cost of backyards – so-called pluzina (Houfková et al. 2015; Sauser et al., 2022; Sklenička et al. 2009, 2014) – of the original plots.

4. Discussion

The Czechia is, from the perspective of the typology of rural settlements, an exceptionally interesting and varied territory. Individual settlements reflect the morphological, cultural, and historical associations and conditions for agriculture, providing a multitude of information on the history and past life in these settlements and being of high cultural and urbanistic value. A similar typology can be implemented outside of the Czechia as well – at least in the Central Europe with similar historic development.

4.1 Classification system

Several classification systems have been published in Czech in the past (Kuča 2009, 2013; Máčel 1955; Pešta 2000; Škabrada 2022) but were typically too complicated for practical use. On the other hand, papers analyzing the historical layout structure published in the international literature – for example: (Kostof 1991; Major and Dalton 2018; Marshall 2004) – typically used only dichotomous classification, which does not support a complex evaluation, either. The presented classification system offers a suitable compromise between these two approaches. While remaining relatively simple, it allows for a functionally complex assessment that takes into account not only the geometric layout of the settlement, but also its urbanistic structure, its relationship to the surrounding agricultural landscape, and its capacity to spatially integrate or clash with newly developed parts. This broader view of complexity reflects the changing dynamics of rural areas under suburban pressure and provides a framework for analyzing whether traditional and new structures coexist as a coherent whole or result in spatial fragmentation. This system, although applied to the region of the Czechia only in this paper, is likely applicable also to other (not only) Central European countries; with minor adjustments, it could be applicable also to other European countries and for AI-based classification over large areas.

4.2 Settlement classification according to the historical structure

Square-type settlements are the oldest form of settlement layout. It is most represented in the central and eastern parts of the Czechia, i.e., in the parts where colonization occurred in the earliest times of all regions within Czechia (before the 12th–13th century). This is thanks to their favorable physical-geographic conditions (lowlands, near major rivers) facilitating agriculture, which represented the dominant economic activity of the time (Sádlo et al. 2005). Stripe-type settlements dominate in the areas that were colonized later (14th century), when forests were cleared and less favorable hilly and submontane regions were colonized (Kučera and Kučerová 2009; Kuna et al. 2004; Škabrada 2022). Dispersed layouts are typical of montane regions where the individual objects are at greater mutual distances due to the terrain morphology. Plot-type layout is a newer settlement structure developed from stripe-type. These settlements originate predominantly in the 18th century when large farms were split into plots of unified sizes and distributed among small farmers, which led to the formation of relatively smaller settlements with regular layouts.

4.3 Classification of new developments according to street network structure

The new developments mostly differ from the original core structure of the settlement in their layouts, not supporting the formation of full-fledged centers. Moreover, the permeability between the new developments and historic cores is often limited (Fig. 6b) and these new developments are typically accessed by a road (or roads) oriented on the main road leading towards the autonomous center (Fig. 6a, b).

This way of the construction of new developments is not specific to the Czechia – it can be rather observed globally (Moudon and Hess 2000; Scheer 2001; Southworth and Owens 1993). Should we classify the new developments in the same way as the historical cores in the previous part of the paper, all these settlements would be characterized as the plot type (Pešta 2000). This predominance of plot-type

structures disregarding the associations with the surrounding landscape is highly typical of new developments in suburbanized areas. In many cases, new developments are attached to the existing structure without forming spatially coherent centers, which limits permeability and functional integration (Maňas 2020, 2023).

New developments often suffer from urbanistic and architectural heterogeneity, especially when not arising as a single large development but rather as gradual (although turbulent) growth (Fig. 6b). This results from differences in plot sizes, architectural solutions, regulations, and land use planning restrictions valid at different time points. This combination of factors leads to differences in the readability of the space for the users as well as of the plans for the regulatory authorities.

4.4 Ornamental urbanism

The new developments are often not shaped strictly geometrically or organically. Larger new developments are often characterized by something we can call "ornamental structure". Although not part of the formal classification system presented in the Results, these patterns were repeatedly observed during visual analysis and are here introduced as a reflective interpretation. We can, therefore, speak of "ornamental urbanism" that can be easily identified in the layout or on an orthophotomap (it may be difficult to recognize when viewed from the users' perspective, i.e., from the street). Such ornaments can consist of geometric or organic street layouts as well as their combinations. These forms are not proposed as a new typology but rather as a discussion point emerging from observed tendencies in larger suburban expansions. Such ornaments are more typical of large new developments in which the urban planners' creativity and invention could have been applied to a greater degree; at the same time, however, it is necessary to take the original layout and historical core into question and to sensitively connect the old and new developments to prevent the disruption of the original layout and architectural structure by the new development (Baše 2004, 2006; Cílek and Baše 2005; J. Sýkora 1998).

4.5 Unsuitable connections and risks

The ability of different historical settlement types to integrate new development without compromising their original structure varies significantly (Baše 2002a, 2004). In square-type settlements, the original compact core remains visually and functionally distinct, even when new development is added. In contrast, stripe-type settlements tend to expand through additional streets placed behind the original plots. This pattern, often combined with the reduction of plot sizes, can blur the distinction between the historical core and the new extensions.

If not sensitively planned, such extensions may result in the gradual obscuring or fragmentation of

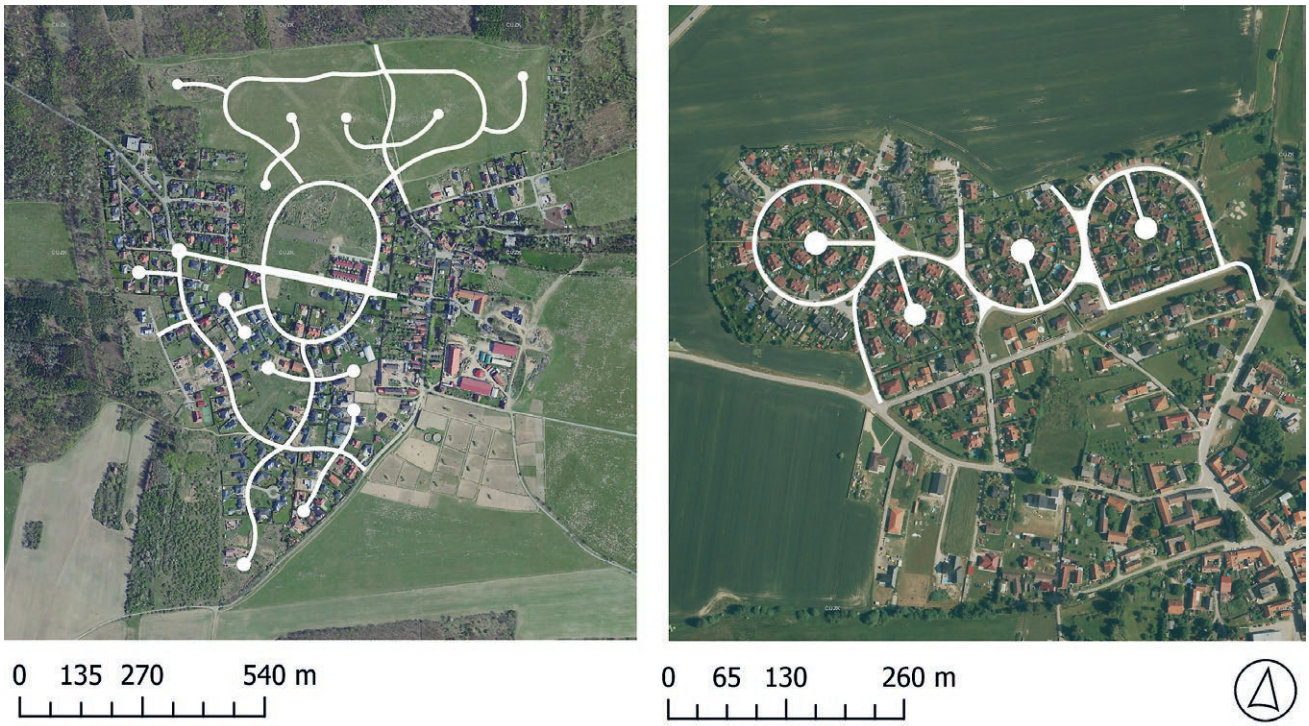

Fig. 7 Examples of ornamental street layouts in two settlements, left: the future development plan in the village of Trnova; right: the realised expansion in Dolní Třebotín. Orthophoto data sourced from the State Administration of Land Surveying and Cadastre 2023.

the original spatial structure. This is particularly problematic when new buildings are constructed directly in former backyard spaces, which historically served as transitional zones between built-up areas and the open landscape. The loss of this buffer can diminish the rural character of the settlement and reduce the legibility of its historical form (Foley and Scott 2014; Scott et al. 2019).

4.6 Possible measures

To preserve the distinctive character of the rural settlements, i.e., to prevent damage by new developments – urban sprawl; (L. Sýkora and Mulíček 2014; Zabik and Prytherch 2013) – the scale and layout of the development must be taken into account. It is advisable to look for spatial reserves in the existing settlement core (e.g., ruins, brownfields) before resorting to creating new developments outside the original settlement layout. If this is done, it is advisable to follow urban design principles based on the settlement pattern.

Where it is necessary to create a new development in the vicinity of the original core structure, it is beneficial to prevent their direct adjacency. Suitable solutions might include a gap (e.g., a narrow park or a boulevard-type street) supporting the growth of tall greenery (Maňas et al. 2023), which can visually separate the buildings characteristic of the core from new developments that are typically of different architectural design and will support the good visual appearance of the settlement. In addition, such a gap will also create a public space suitable for mixing of original and new populations and provide a cooling effect (Maňas 2023).

4.7 Study limitations

The subsample of 60 analyzed settlements is small for making any strong statements about the general character of suburbanized settlements in the Czechia; it is, however, intended rather as a starting point for opening discussion on the topic of the optimization of the development of rural settlements with high urbanistic and cultural value. This subsample can also serve as a pilot study for further research that could utilize artificial intelligence for the identification of new structures and their classification (manual classification would be extremely time-consuming due to the large number of settlements).

5. Conclusion

The presented study introduced a simple classification system of small settlements based on their historical layout and classified all settlements in the Czechia according to his system. Subsequently, on a subsample of 60 suburbanized settlements of village-square type or stripe-type, which dominated among suburbanized settlements, we analyzed the street network layout and adjacency of the new developments to the core. We ofound that most new developments among the analyzed settlements have geometrical street network. The mutual proximity between the new development with geometrical street network and original core with valuable layout structure can lead to the destruction of characteristic features of the original typological groups of rural settlements that allow the identification and cahracterization of their cultural-historical development.

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Volunteering with refugees in Czechia: From traitors to heroes?

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ABSTRACT

This article examines the experiences of volunteers (N=12) engaged with migrants in Czechia. It evaluates their roles during two different refugee crises which affected Czechia in 2015/2016 and in 2022. The starting point for the study was a difference in public attitudes towards migrants and refugees during these two refugee inflows. While negative perceptions were evident during the 2015/2016 refugee crisis, characterized by scepticism and resistance toward volunteerism, the response to the Ukrainian refugee influx showcased a more supportive environment, potentially influenced by institutional aid efforts and a greater sense of solidarity with Ukrainian refugees. We conducted semi-structured qualitative interviews with volunteers engaged in the 2022 refugee crisis, some of whom had a previous volunteering experience from 2015/2016. The article reveals individual experiences of volunteers, their positionality, coping strategies and different perceptions of migration contexts.

KEYWORDS

attitudes; Czechia; migration; refugees; volunteering

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1. Introduction

Contrary to initial expectations, Central and Eastern European states demonstrated swift responses to the 'crisis' stemming from the conflict in Ukraine in 2022. As the European Union decided, for the very first time, to activate temporary protection through Council Implementing Decision (EU) 2022/382 of March 4, 2022 (European Union 2022), Czechia subsequently established a temporary protection framework aimed at assisting all incoming refugees, which has been framed in special 'Ukraine' Acts (Acts no. 65, 66 and 67/2022 Coll., regularly updated according to the evolution of the conflict; Elektronická Sbírka zákonů a mezinárodních smluv 2024a, 2024b, 2024c). With about 520,000 Ukrainian refugees for 10 million of inhabitants (UNHCR 2023), Czechia emerged as the host to the largest population of Ukrainian refugees per capita.

It has to be said that there could be some mostly historical reasons behind the rationale of so many Ukrainian refugees choosing Czechia instead of other countries. In the 19th century, both western Ukraine and present-day Czechia were part of the Austro-Hungarian Monarchy, fostering long-standing ties between the regions. Notably, Transcarpathian Ukraine was incorporated into interwar Czechoslovakia. Political, and to a lesser extent economic, factors drove Ukrainian emigration in the early 20th century, with Czechoslovakia emerging as a key destination. Before World War II, approximately 6,000 Ukrainians had settled there, including army officers, politicians, intellectuals, students, and impoverished peasants (Drbohlav and Seidlová 2016). They established a range of institutions spanning politics, culture, education, and science, supported by the Czechoslovak state. Following World War II, many Ukrainians who opposed the Soviet regime left for Germany; others were imprisoned after being deported to the USSR. By 1948, all Ukrainian organizations in Czechoslovakia had been shut down (Drbohlav and Dzúrová 2007). During the socialist era (1948–1989), Czechoslovakia's restrictive immigration policies led to minimal (Ukrainian) migration.

The Velvet Revolution of 1989 marked a turning point in Czechia's migration landscape, initiating democratic and market reforms that opened the country to global mobility. As Czechia evolved from a transit zone to a net immigration country – particularly after joining the European Union (EU) in 2004 – migration flows intensified. Among immigrant groups, Ukrainians played a central role: their departure pressures aligned with Czechia's labour demand and liberal migration climate, making them a dominant force in the post-1990s immigration boom (Seidlová 2018). At the end of the year 2021, about 661,000 of immigrants lived in the country (making up about 6% of the population of Czechia), Ukrainians being the most represented ones (197,000 – 30% of immigrants), followed by Slovaks (114,000 – 17%) and Vietnamese (65,000 – 10%; MVCR 2024a).

In what concerns the migration policy with regard to the refugees, Czechia has traditionally applied a restrictive policy in terms of granting asylum or international protection. Of 99,352 persons who applied for such status between 1993 and 2021, only 3,499 (i.e. 3.5%) received it (MVCR 2024b), which obviously translated into a very small number of refugees living in the country.

The implementation of the Temporary Protection Directive in 2022 resulted in a highly unprecedented situation, characterized by both the exceptional number of refugees entering at one moment and remaining in the country – while being mostly women and children – and the notably receptive stance adopted by public administration. At the same time, the seemingly 'forced' or 'imposed' welcoming attitude toward Ukrainian refugees was nonetheless met with a degree of public understanding. This response was shaped not only by the cultural proximity that many Czechs perceive in relation to Ukrainians – reinforced by prior experiences with already settled Ukrainian migrants – but also by a sense of shared historical memory, particularly the collective trauma associated with the 1968 Warsaw Pact invasion led by the Soviet Union.

In this newly formed migration environment, we decided to further explore the perspectives held by the primary civil society actors engaged in providing assistance to refugees which became a pertinent endeavour. Still, it is important to note that the influx of Ukrainian refugees occurred against the backdrop of ongoing arrivals of asylum seekers from other parts of the world (MVCR 2024c). Grassroots or bottom-up initiatives that extend aid to refugees play a pivotal role within the realm of civil society organisations. Research shows that volunteer efforts play a vital role in fostering civil solidarity and mutual assistance (Madryha et al. 2024). We understand volunteer roles as various responsibilities and functions undertaken by individuals who offer their time and effort without financial compensation to support refugees and migrants. These roles can range from direct service provision (e.g. interpretation, distribution of aid, emotional support), to organizational tasks (e.g. coordination, logistics, outreach), and can occur in both formal institutional settings or informal grassroots initiatives.

This significance of volunteer efforts is even more pronounced in environments that exhibit a certain degree of hostility toward their humanitarian efforts, as was notably witnessed in the Central and Eastern European countries during the refugee situation of 2015/2016 (CVVM 2019; CVVM 2023). In this period, individuals who were not indifferent to other peoples' situations started forming informal networks that later developed into humanitarian actors attempting to help people on the move in the Balkans (PLNU 2024).

In 2015, over 1 million migrants from the Middle East and Africa entered Europe via Southeastern Europe. Transit countries initially enabled this movement, creating the so-called 'Balkan corridor' (Jochim and Macková 2024), where many volunteers assisted. This situation was fuelled by conflicts in Syria or Afghanistan but also political persecution and instability in various countries.

This paper draws upon interviews conducted with individuals actively involved in the current Ukrainian refugee situation in Czechia, which will be further referenced as 'crisis' or 'situation' or 'crisis situation'. Some of these volunteers were also active in 2015/2016. Comparing the attitudes in both 'crises' situations was made possible by the fact that the volunteers from 2015/2016 were our students or acquaintances, or other volunteers they knew well, so we were able to keep in touch with them. The paper aims to explore how the roles of volunteers with migrants and refugees can be shaped by various socio-political and institutional contexts and how they perceive different migration situations and their dynamics. Furthermore, this research probes whether the response to the Ukrainian refugee 'crisis' can be viewed as a continuum of the prior grassroots initiatives that aided refugees from the Middle East. In doing so, it endeavours to answer the following critical questions: What were the experiences of the volunteers and their positionality? Which differences do they perceive between both 'crisis' situations in terms of migration contexts and public discourse?

2. The context on volunteering with migrants including refugees

The environment of working with migrants has been described as 'hostile' in Central and Eastern Europe (Zogata-Kusz 2022). During the refugee situation of 2015/2016, volunteers were described as 'welcomers' or 'sunny people' in Czechia ('sunny' meaning a person who is more open to the world and left-leaning, pejorative term, mildly insulting or rather contemptuous; Trachtová 2015). These volunteers played a crucial role in providing aid and support to migrants, with some even departing for the Balkans to contribute to relief efforts through organisations like *Pomáháme lidem na* útěku (PLNU; the name translates into 'We help people on the move') and others. Notably, volunteers also organised material assistance initiatives, such as those seen at Autonomous Social Center named 'Klinika' in Prague (translates into 'Clinic', based on the place of operation – in a former pulmonary clinic) and similar organisations. Interestingly, it has been argued that individuals opted to leave their home country for a short term and volunteer abroad as a form of compensation for what they perceived as unfavourable Czech state policies (Křeček 2016). These solidarity practices evolved into a social movement of like-minded individuals.

Later on and in a different refugee context the act of 'volunteering' has evolved and has been officially recognized and institutionalised during the Ukrainian refugee situation. National and local authorities even appealed to the citizens to accommodate the refugees from Ukraine (see, for example, Seifert 2022). At same time, many citizen platforms had arisen and acted like coordinators of the helping activities for the refugees before the official authorities were able to do so (Švihel 2022). This shift reflects changing dynamics in the response to humanitarian crises and the integration of grassroots efforts into broader, more structured relief initiatives.

Globally, civil society organizations – where the majority of volunteer work is carried out – are generally focused on fostering equitable and sustainable social development, with the shared goal of making the world a better place (Vermeersch 2004). This mission is driven by individuals with good will, who feel a sense of responsibility toward their community and contribute through their time, skills, expertise, and sometimes even material or financial resources (Manço and Arara 2018). These so-called shadow citizens, motivated by a desire to foster mutual aid and collaboration among people, aim to transcend profit-driven motives and competition, working instead to strengthen the common good; and many of them do so as volunteers (Dubost 2007). Volunteers exchange their unpaid commitment for personal fulfilment, self-actualization, and a sense of balance in their lives, often seeking out social connections as well. The range of voluntary work is diverse, encompassing activities from organizing local leisure events to offering services such as legal guidance, professional training or social support (Manço et al. 2021).

According to the framework proposed by Clary and Snyder (1999), volunteering fulfils six core functions: values, understanding, enhancement, career, social, and protective functions. These roles provide a comprehensive lens for understanding the varied motivations and impacts associated with volunteer work (see also Haski-Leventhal et al. 2011 and Nesbit et al. 2018). Duguid et al. (2013) emphasize that volunteering not only benefits the recipient organization and its audience but also brings positive outcomes to the volunteers themselves. For example, volunteer activities can reinforce volunteers' personal identities, enhance their social networks, and develop their skills (Meyers 2006). Viewed as a form of informal education, volunteering enables individuals to gain knowledge and valuable social and professional experience. Other benefits include building qualifications, fostering a sense of usefulness and self-efficacy, enhancing self-confidence, and maintaining work habits (Frič 2001). Furthermore, volunteering can address psychosocial challenges, offering a means to empower and support the integration of migrants as

they settle in their host countries (Valentová and Justiniano-Medina 2019).

Volunteering plays a significant role in promoting social integration, particularly through its interactive dimension, which highlights the active participation of immigrants in relationships and in the private aspects of the majority society's social life (Heckmann and Schnapper 2003; Bosswick and Heckmann 2006). In this context, volunteering can act as a protective barrier against social exclusion for vulnerable groups, including migrants (Čamlíková et al. 2015). Since the early 2000s, numerous European initiatives have identified volunteering as both a tool and an indicator of social integration, political participation, and economic engagement, especially concerning immigrant communities (CEV 2006).

Nonetheless, it is important to note that migrants have often been portrayed as passive recipients of volunteering efforts in various contexts, as observed by Ambrosini (2020). This perception suggests that migrants typically receive volunteer support without actively contributing to or influencing the goals of volunteer activities. However, an emerging perspective known as citizenship from below offers a different view. Scholars such as Ambrosini and Baglioni (2022) and Ambrosini and Artero (2023), when discussing the case of Italy, highlight a new paradigm wherein migrants are recognized not only as recipients but also as active participants who contribute to and help shape volunteer initiatives. This grassroots form of citizenship reflects the evolving role and agency of migrants within the volunteer sector, challenging traditional views about their involvement in volunteer efforts.

Moreover, the dynamics of its frontiers, even in Europe at its most oppressive, have always been about the differential closing and opening of borders (Favell and Hansen 2002). At the same time, the boundaries can be also symbolic, framing the understanding and using of three most commonly used terms for people living outside their country of origin: foreigner, migrant, and refugee. According to the recent work of Rapoš Božič et al. (2022) on the Czech context, the label foreigner calls upon legal and cultural criteria, whilst the labels migrant and refugee involves moral criteria. We also use the label 'refugee' to refer to the temporary protection holders as a shortcut for this designation while understanding it is not a proper legal category in this context. At the same time, there is a strong political and media narrative which suggests that even where people have been forced to leave their countries due to conflict, persecution and human rights abuse, they should remain in the first countries to which they arrive rather than making the hazardous journey across the Mediterranean to Europe (Kuschminder and Koser 2016). Their decision to do so is viewed, under the false pretext of the 'first safe country' clause, as confirmation that they are 'migrants' rather than 'refugees', and therefore, undeserving of protection.

3. Methods

Between March and June of 2023, a comprehensive study was conducted involving in-depth semi-structured qualitative interviews with a diverse group of 12 volunteers. Our students and/or acquaintances, or their close contacts, involved in volunteering in the 2015/2016 situation, made up about one half of our respondents. Thanks to them, we also received the contact information of other volunteers, involved only in the situation of 2022. The interviews spanned a range of durations, lasting from 30 to 70 minutes, allowing for a nuanced exploration of their experiences and perspectives. A few interviews took place online based on participants' request, while most were taken in person. In both cases, the interviews were recorded – with the help of mobile phone if taking place in person, or directly with the help of Zoom application while taking place online.

To analyse the data collected from these interviews, we firstly transcribed the interview recordings and translated them into English. Then we employed qualitative data analysis which meant coding the acquired information in the first place. The tool used for coding was Atlas.ti software. In terms of concrete research design, we have chosen thematic analysis. This thematic analysis was chosen to enable the researchers to identify recurring themes, patterns, and insights within the interview transcripts (Terry et al. 2017). This analytical approach ensured that the study's findings were grounded in the rich and nuanced perspectives shared by the volunteers. The codes were merged into seven different categories by the researchers, namely i) Emotional Responses, ii) Support Systems and Coping, iii) Perceived Deservingness and Judgments, iv) Social Categories and Identity, v) Politics and Institutions, vi) Migration Context and vii) Public Discourse. As an example, the codes under i) Emotional Responses included words such as anger, anxiety, burnout, emotions, fear, guilt, helplessness, hope, hopeful, joy, negative affect, positive affect, resilience, sadness, trauma, worry. Related categories were grouped into overarching themes through iterative review and team discussion. The themes are volunteers' positionality, emotional responses and coping strategies, and perceptions of migration contexts.

Ethical considerations were paramount throughout the research process. Prior to conducting the interviews, informed consent was obtained from all participants, ensuring that they were fully aware of the study's purpose, the nature of their involvement, and their rights as interviewees. Furthermore, participants were assured of their anonymity and confidentiality, with pseudonyms (such as R1, R2 etc.) used to protect their identities in any subsequent publications or presentations of the research. Additionally, throughout the interviews, sensitivity was used in order to ensure that participants felt comfortable

sharing their experiences, particularly when discussing potentially contentious topics related to migration and volunteering in 'crisis' situations. Next, we will discuss the results of our study, including the perceived difficulties by the volunteers, differences perceived in both situations and attitudes towards their work.

Within this sample of volunteers, there were distinct categories of engagement. Mostly those who were involved in helping in the Regional Ukrainian refugee centres (see below) were 'new' volunteers, who did not help in the situation of 2015/2016. In concrete terms, seven volunteers dedicated their efforts exclusively to the ongoing Ukrainian refugee situation. Among them, only some of them were present in Czechia during 2015/2016. Five individuals had previously volunteered during the 2015/2016 refugee situation and had returned to volunteer once more in the current Ukrainian context, providing valuable comparative insights into the evolving landscape of volunteerism. We understand the limitation of the sample and the different experiences for those who only volunteered in 2022. However, this study enables us to explore experiences of volunteers in migration contexts and to show their positionalities at different points in time and across different geographies.

The interviewees represented a balanced gender distribution, with seven women and five men participating in the study. This gender diversity within the sample enriches the study's exploration of volunteering experiences. Additionally, there is one kind of interesting gender imbalance in the sample: the majority of Czech respondents are men (five out of six), while the rest of the participants are all women. This may also introduce certain biases into our findings. The women who volunteer may face different expectations from their roles and they may experience situations differently than their male counterparts. They may also face different circumstances (such as caring for family members) which may make volunteering more difficult for them than for men (Taniguchi 2006).

There is also the geographical diversity of the participants, with six volunteers hailing from Czechia, four from Ukraine, one from Russia, and one from Slovakia. The volunteers were either students at the university or they had already finished their university degree and worked full-time in their regular jobs. Their ages ranged from 20 to 43. In 2015/2016, volunteers outside of Czechia often operated informally, responding to needs as they arose, without formal written contracts. In contrast, due to the legal regulations governing volunteer work in Czechia, volunteers working within the country were required to have a formal volunteer contract with the organization they represented; however, the aim of this contract was only to provide them with some kind of insurance (if they cause for example some unintended damage) and not a financial compensation, i.e. they dedicate their time for the organisation in question for free. However, some 'volunteer translator' positions in KACPU (Regional Ukrainian refugee centre) developed into paid positions later. The respondents resided in different regions of Czechia at the time of interview, most of them in the Olomouc Region (8) and in Prague (4). This diverse representation allows for a range of volunteer experiences. The background of interviewees is shown in Tab. 1. The recruitment process for interviewees employed a snowball sampling technique, leveraging existing connections and organisational networks within the volunteer community. This approach ensured that the participants had relevant experiences and insights to share.

Tab. 1 List of interviewees.

Respondent	Gender	Nationality	Volunteering/coordinating activity
R1	F	Ukrainian	Regional Ukrainian refugee centre
R2	F	Russian	Regional Ukrainian refugee centre
R3	M	Czech	PLNU + transport from Ukraine
R4	F	Ukrainian	Regional Ukrainian refugee centre
R5	F	Ukrainian	Regional Ukrainian refugee centre
R6	F	Ukrainian	Regional Ukrainian refugee centre
R7	F	Slovak	PLNU + Regional Ukrainian refugee centre
R8	M	Czech	PLNU + NGO "People in need"
R9	M	Czech	Regional Ukrainian refugee centre
R10	M	Czech	PLNU + transport from Ukraine
R11	M	Czech	Koridor UA
R12	F	Czech	Regional Ukrainian refugee centre

NB: PLNU – "Pomáháme lidem na útěku" (Czech NGO whose name translates into "We help people on the move"); Koridor UA – "Humanitární koridor na Ukrajinu" (Czech NGO whose name translates into "Humanitarian corridor to Ukraine"). Source: own research.

4. Results

4.1 Volunteers' positionality

The attitudes toward volunteering differed markedly in both situations. In 2015/2016, many volunteers experienced anger aimed at them or their work. They were even labelled as 'traitors' by some people. However, at the same time, they believed that they did the right thing, which helped them face the challenges. The different framing of their experience might come from differences in public perceptions of solidarity and who is seen as deserving of assistance. The volunteer below describes how mundane tasks such as operating a laundry room became political because of the narratives in the Czech society.

> [The situation] completely escalated by both sides as a hero for one, a traitor for the other. […] I was seen as a traitor, even if the only thing I was doing was keeping the washing machines running. We had a laundry room and the system put in place was that people – you know, that refugees – received tokens, they went there and simply washed their clothes there for those tokens. Me and my colleagues, we basically only cleaned and repaired the washing machines and simply kept the laundry room running (R8).

The spatial detachment of the 2015/2016 volunteering context outside Czechia, combined with prevailing media discourses, created a disconnect between the volunteers and their local environments. Volunteers often found themselves having to justify their efforts, emphasizing the importance of assisting those in need. In contrast, at the onset of the Ukrainian situation, such explanations were largely unnecessary. In this case, volunteering was treated more favourably with some volunteers even being described as heroes by their friends.

> My friends actually told me… I was a hero. […] The Czech Republic doesn't owe anything to Ukraine to help. But I think it's great that solidarity has been created (R5).

In general, volunteering in the current Ukrainian situation sparked curiosity among the friends and family and did not lead to any serious confrontation for the interview partners. The interviews included mentions of appreciation from friends and relatives for their involvement.

> When it comes up, they react very positively and they're curious about what it's like [to volunteer at KACPU]. […] So then they were totally texting me, like, it's so great that I'm helping out there (R2).

There was also the geographical aspect of volunteering closer to home which was perceived as safer. Yet, some volunteers ventured outside of Czechia, and this was seen as dangerous.

> Positive, more or less positive reaction or negative reaction in that people thought it was stupid to go straight there [to Ukraine] and that it was dangerous and so on. It was from the family side, but especially when we returned safely afterwards, they felt like we had done a good thing (R10).

However, with passing time, some volunteers also remarked on general tiredness and decrease in support towards the Ukrainian situation (and by extension, volunteering in this context).

> The reaction of the people around me was initially excellent, but as expected, it wasn't surprising at all, it just started to wane. And also simply because the classic 'what about me'-ism came. But also because there were more cases of some negative experiences, that it happened, I don't know, someone stabbed someone in a hostel or stole something. Again, a normal thing but […] with the social networks it just got bigger than it was probably in reality, so then this kind of thing started […], or that they [Ukrainians] get various discounts, that they get free travel, and so on (R7).

The temporal dimension played a significant role in the Ukrainian refugee response, with some volunteers observing a decline in public support over time – contrasting sharply with the initial weeks and months, when their efforts faced little to no opposition. However, the perception of the Ukrainian situation was much better than the 2015/2016 situation and it also points to the perceptions of solidarity and refugee deservingness in the general society.

4.2 Emotional responses and coping strategies

There were different emotions that volunteers identified as challenging in both situations in 2015/2016 and 2022/2023. For example, volunteers experienced stress, fear, sadness, and guilt. Some felt guilty primarily because they were in a safe environment while witnessing the suffering and challenges faced by migrants or their friends and family in conflict or 'crisis' situations. This guilt stemmed from a sense that they felt they should be doing more to help and make a meaningful contribution rather than merely acknowledging their own safety or comfort. Respondent 5 recalls:

> But the full-blown war started, and I felt guilty about being safe, so I thought about what I could do. […] All my friends and family were in Ukraine and I could just share [how I felt] with them, but it seemed unfair to me as well. Just kind of complaining that I have a hard life and [they]'re in Ukraine (R5).

The sense of guilt was also present in the other refugee context when some participants mentioned that their privileges such as having the EU passport and being able to travel freely across the borders gave them the obligation to help. In both contexts, the encounter with conflict situations and displacement underscored the importance of volunteers' roles not only in providing practical assistance but also in offering emotional support and empathy to those affected by the traumatic consequences of conflict and forced migration. These experiences had a lasting impact that went beyond the immediate volunteering engagement.

> The trauma […] came to me after six months, a year, and after that it seemed to fade away. It was really very, very demanding to work there, but I guess the main motivation was that you put your hand to the work, and that it was so [geographically] close, so I just couldn't let it go… That people were simply running away, they had nowhere to sleep, we simply couldn't let it happen (R7).

Some people who volunteered in 2015/2016 referred to experiences they witnessed while volunteering and even years later, the emotions like sadness resurfaced.

> Well, coming back there like a year later, when I was supposed to talk about it, I just had tears in my eyes, it was just really bloody difficult, it was like actually it didn't really sink in at the time, we were unmoved by something like that, for me it was just the first crisis like that, so I actually thought what we were doing was normal, but when I saw the experienced ones, when the others came, they were [exclaiming] Jesus f*cking Christ (R8).

While it seemed that the situation was harder for the volunteers in 2015/2016 when the support was less institutionalised, people also encountered difficult moments in 2022/2023 when they witnessed some situations first hand. The volunteers recall these encounters.

> I had a situation where I was interpreting at the psychosocial centre and there were a few old age pensioners sitting there and they were talking about how they were hiding in the basement and suddenly I thought… Well, I can't repeat it in Czech because I'm going to cry and I just… Well, so I told the psychologist that I'm so sorry but I'm not going to interpret it, it's like too much for me (R5).

There were different approaches to dealing with the emotionally laden situations. While the volunteers in the Ukrainian refugee situation mentioned psychologists being present in the centres and helping them to discuss any problematic situations, this was rarer in other refugee situations (R3). Some volunteers appreciated the professional psychological support. However, others did not find it as useful as sharing among their friends. This collective coping was often mentioned by volunteers in both situations.

> Actually, not only me, but also others felt that it didn't help us at all. We felt that it would help us if we went out to a pub in the evening or went for a coffee somewhere. That would help. It could be a friend or someone close to me and she would tell me and I would tell her, we would talk together and we would move on, rather than some psychologist I'm seeing for the first or second time in my life and he would just say "well, yeah, talk to me". […] A shower always helped me. But at the beginning it was quite challenging because at work you control your emotions and you just come home, like everything (comes out) […] but that's fine because it kind of goes away and that's it (R4).

Even without the institutionalised setup, some volunteers in the first 2015/2016 situation felt the need to find professional support such as a psychologist to deal with the situations they encountered.

> We had some kind of attempt to systematically set up psychological help for people (when volunteering in 2015/2016). Then I was in a few sessions, like a group therapy, and since then I've started going to therapy too as an individual. With greater or lesser intensity depending on how necessary it is. […] I simply came, I wanted to go to a pub in the evening, I looked at people there, like what on earth are you talking about, about the cinema, about going to buy some shoes… so I finished my beer and left (R8).

Others also described "switching off" and emotionally detaching from the situations.

> In general, the environment is so demanding, it probably affects some people more, some less. I don't know, I dealt with it a lot, that there is a lot of drinking, alcohol and such, to switch off the evening. It definitely affected me, especially those stories […]. Now when we went to Ukraine, it was actually… like some numbness… we crossed the border, now there were people standing at the crossings… a kilometer long queue of people and it didn't even affect me that much. I thought to myself 'well, more refugees'. And you defend yourself with that cynical attitude, that it doesn't affect you that much. Partly it's good, partly it probably isn't (R3).

Therefore, volunteers in both situations encountered difficult moments that were emotional and had to deal with them using different strategies. The mixed emotions did not fade with time for volunteers in 2015/2016 and they had to cope with them even later. We do not know about any lasting impact of the 2022/2023 situation as it was still ongoing at the time of research. However, some seasoned volunteers described emotional detachment affecting them

less in the second situation after they have gained experience from previous crises. Many volunteers also recalled using psychological help or coping collectively their peers to help them overcome difficult situations.

4.3 Perceptions of migration contexts and public discourse

Public discourse on migration was shaped by differing perceptions of solidarity and who was deemed deserving of support. The context of both situations differed markedly. With the political will to accept Ukrainian refugees came also institutionalization of centres for Ukrainian migrants (KACPU) in all regions of Czechia. These centres required volunteers for their daily operations. In contrast, the irregular transit migration context of 2015/2016 created a fluid and non-institutionalised environment that changed frequently based on the migration flows and volunteers outside of Czechia were only able to commit for a set period of time ranging from days to weeks.

Borders played an important role in this context. While the EU borders were closed to everyone outside the EU in 2015/2016 resulting in a 'game' when trying cross (Minca and Collins 2021), in 2022, the borders suddenly opened for Ukrainian 'third country' nationals while leaving some non-European migrants behind (Ojwang et al. 2024). The porousness of EU borders for some groups of Ukrainian refugees (with the exception of some men who were required to stay because of the conscription) contrasted sharply with the closed Polish Belarusian border for refugees who were seen as more politicised and less deserving (Grześkowiak 2023).

Against this backdrop, volunteers mentioned the role of the media as an important contributor towards the perception of both refugee situations. How people on the move were portrayed and their gender (even though the media could not portray the situation in a holistic way) proved significant in showing favouritism towards certain groups. In the words of respondent 7, referring to the Ukrainian situation, 'they're just like that, fragile young women with those little children and those mothers.' This echoes the portrayal of 'womenandchildren' as a category that is omitted in the securitization discourses (Enloe 2014). Participants also mentioned political parties that, during the 2015/2016 crisis, sought to gain electoral advantage by capitalizing on the migration issue. In that time, populist radical-right parties like France's National Rally, Germany's AfD, Italy's Lega or Hungary's Fidesz benefited from the 2015 crisis – while overall public attitude did not drastically shift, rightwing voters hardened and electoral divisions widened (van der Brug and Harteveld 2021). In Central European context, parties such as Polish PiS, Czech ANO or already above mentioned Hungarian Fidesz moved sharply toward restrictive immigration positions after 2015, correlating with electoral gains (Ivanov 2024). A discourse analysis of Czech parties' manifestos for the 2014 and 2019 European Parliament elections reveals that migration had already been framed in security terms before 2015, but the 2015–16 crisis intensified the securitization rhetoric. This framing was adopted pragmatically across the political spectrum, not limited to extremist populists (Krotký 2019). Despite low refugee numbers (circa 1,500 in 2015), prominent figures such as President Miloš Zeman referred to an "organised invasion" in December 2015. Far-right leader Tomio Okamura secured over 10 % of votes in 2017 campaigning against the "Islamisation" of Czech society (Saxonberg, Sirovátka and Csudai 2024).

> In 2015/16 I would say, it was still politically amplified, even in the media. Today, I don't know, even the SPD [far right party] is not so strongly against the aid to Ukraine. Back then, half of the political spectrum and a lot of the media just played on it, and here the effect has just multiplied exponentially. Today I don't think it has as much support, although a little bit, but not as much. And so that's why it was stronger than it is now. And moreover, with the Ukrainians, the people have very close experience, they can touch it, they are [culturally] closer, they do not feel some kind of threat (R3).

The quote above also elaborates on perceived cultural closeness between the Czechs and Ukrainians and previous historical ties between the countries. It is clear that because of this shared recent history, many Ukrainian refugees chose Czechia (or Poland) as their destination. This perceived cultural similarity was also highlighted by the volunteers.

> The cultural proximity, the linguistic proximity. One hundred percent, it played a role that just like there was a Ukrainian community here and everybody knew some Ukrainians and had some experience with something, whereas with Syrians they just didn't exist before, like that, the situation was very, very different in that way, and humanly, understandably, I was already angry at everybody in that year 2015 (R8).

Finally, volunteers were aware of the historical experience of Czechia with the Russian occupation in 1968 and the shared aggressor, which made the plight of Ukrainian refugees more relatable to the public.

> Then I would say that in the case of the aggression in Ukraine, the fact who the aggressor is, also plays a role. Because I'm sure for a lot of Czechs it's a trigger, just a trigger of 'oh, Russia' so there it probably wouldn't matter who Russia attacked anymore, it would just be that Russia is the aggressor. I don't know if there would be the same reaction if Ukraine was attacked by the US or Lithuania or just someone we basically know nothing about. I don't know, maybe I'm wrong, maybe it would be exactly the same, but the role of Russia is also important (R2).

Therefore, the volunteers are aware of the differences in the migration contexts but stressed the role of the media and some political parties as important during the migration contexts. They also discussed the perceptions of shared migration history and cultural similarity between Czechia and Ukraine. Importantly, respondents also emphasized the perceived unequivocal role of Russia as the aggressor and the relative simplicity of the conflict and the narratives around it, which made it easier for the public to understand. As one respondent put it: 'The conflict is simply different, it's a different situation, like it's much more black and white than Syria, which was simply terribly complicated' (R8).

5. Discussion

Volunteer engagement in response to refugee situations has exhibited a notable evolution over time, transitioning from a form of protest against state policy to aligning with official institutional aid efforts (Křeček 2016). This transformation underscores the adaptability of individual initiatives, which have operated in tandem with established institutional support structures designed to assist refugees from Ukraine. Amidst this evolving landscape, certain constants persist. One unchanging aspect is the profound personal transformation experienced by individuals who engage in volunteering (Clary and Snyder 1999; Duguid et al. 2013; Meyers 2006). Emotional experiences and different coping strategies become a catalyst for personal growth and change. It remains evident that volunteering is fundamentally driven by internal motivation rather than by external factors or any other incentives, highlighting the intrinsic desire of individuals to contribute to the welfare of others (Nesbit et al. 2018).

Yet, despite the undeniable value of volunteering, it remains a challenging endeavour that impacts the individuals. One crucial lesson learned from both the 2015/2016 and 2022/2023 situations is the pressing need for psychological support for volunteers. The emotional toll of engaging with refugees, witnessing their traumas, and navigating the complexities of humanitarian crises can take a significant toll on the mental well-being of volunteers. Recognizing this, providing psychological support has emerged as an essential element in ensuring the overall well-being and effectiveness of volunteers in both cases. However, some volunteers preferred collective coping with their friends or emotional detachment which may pose difficulties later on.

The policy towards refugees from Ukraine has shifted and so has the public perception of this group of refugees. According to representative public opinion research, undertaken by Public Opinion Research Centre of the Institute of Sociology of the Czech Academy of Sciences, just after the conflict in Ukraine has begun, only 13% of respondents were against receiving or helping the refugees from Ukraine (March–May 2022), while one year later, this proportion doubled to 26% (June–July 2023) (CVVM 2023). Even if this means worsening of public opinion, it is still a high contrast with public opinion about helping refugees in the previous situation in 2015/2016. In 2015/2016, the ratio was completely opposite: more than half of respondents (60%) from the same representative research of public opinion were against helping the people find refuge in Czechia (CVVM 2019).

The situations differed and in 2015/2016, there was an overwhelmingly negative public attitude towards the work of volunteers. However, the volunteers who were active at that time persevered because of their internal motivations and perceptions of justice or fairness. In 2022, there was a broader social consensus on solidarity towards refugees from Ukraine. While migrants are often seen as 'passive recipients' of volunteering efforts (Ambrosini 2020), this research also engaged with migrants who acted as volunteers. Therefore, this is connected with an emerging trend of inquiring about migrants' experience with volunteering (Ambrosini and Baglioni 2022; Ambrosini and Artero 2023). It could be interesting to further explore the role of migrant volunteers in different situations.

The marked disparity in the support extended to individuals with refugee backgrounds from the Middle East compared to those from Ukraine from the point of view of major population can be explained in three ways: firstly, in the overall attitude of state administration (very restrictive refugee policy within the last 30 years versus 'forced' welcoming following activation of the EU directive), secondly, in the perceived cultural proximity (long history of Ukrainian immigration versus no experience with immigrants from Middle East due to the absence of any colonial ties) and shared experience of the same enemy (USSR leading the troops invading Czechoslovakia in 1968 and now post-USSR invading Ukraine), and thirdly in the composition of refugee flows (women with children, opposed to the predominantly male flows in earlier periods). These three factors, together with the game of mass media portraying both crises very differently and hence, shaping public opinion, can explain why the response to refugees was so markedly different.

6. Conclusion

In conclusion, this paper has provided an analysis of the experiences and roles of volunteers engaged with migrants in Czechia during the Ukrainian refugee influx in 2022 and some who assisted in the refugee situations of 2015/2016. Through a comparative approach, the study has illuminated the evolution of volunteerism and the shifting landscape of humanitarian response in Central and Eastern Europe. The findings highlight the crucial roles played by

volunteers during both 'crises', from providing direct aid and support to migrants to navigating the challenges posed by hostile environments, especially in the latter situation.

Volunteers who were active in both situations noted different perceptions of each situation. While negative perceptions were evident during the 2015/2016 refugee crisis – characterized by scepticism and resistance toward volunteerism – the response to the Ukrainian refugee influx showcased a more supportive environment, potentially influenced by institutional aid efforts and a greater sense of solidarity with Ukrainian refugees. The Ukrainian refugee situation was perceived as 'closer' to Czechia, prompting a stronger inclination toward providing help and support. This was especially highlighted by those who volunteered in 2022. In contrast, the 2015/2016 refugee situation sparked polarized reactions, with some volunteers even labelled as 'traitors' for aiding refugees. However, volunteers attributed this shift in perceptions to specific factors, such as historical connections, cultural proximity, and media influence, rather than to a change in attitudes toward refugees. Consequently, further research into the role of media in framing refugee situations across Europe will be essential for understanding this phenomenon, along with studies examining volunteerism among migrant populations themselves.

This study contributes to the existing literature by offering a comparative perspective on two distinct refugee situations, enhancing our understanding of how volunteers' roles, challenges, and perceptions evolve across different contexts. The comparative approach highlights the shifting dynamics of volunteerism in response to different sociopolitical environments, as well as the impact of public sentiment and institutional support on volunteer activities. These shifts highlight how public discourse, historical ties, perceived deservingness, and media framing influence volunteer engagement and societal attitudes toward refugees. This research underscores the importance of fostering supportive environments for volunteers working with displaced populations.

The results of this study should be considered exploratory, offering preliminary insights rather than definitive conclusions. Despite this limitation, the study's strength lies in its in-depth qualitative approach, capturing the nuanced experiences and evolving perspectives of volunteers. Future research could build on these findings by examining larger and more diverse samples to verify and expand upon these insights. In sum, this research provides a foundation for future investigations into volunteerism in refugee contexts, suggesting directions for exploring the complex interplay between media representation, public sentiment, and volunteer responses. Additional studies on the long-term impacts of institutionalized volunteerism and cross-national comparisons of volunteer responses to different refugee populations will further enrich our understanding of humanitarian efforts in diverse crisis situations.

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Mapping Cultural Routes in Kosovo: A case study of Prizren's multiethnic heritage

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ABSTRACT
Kosovo, a small country in the Balkan Peninsula with a rich and diverse cultural heritage, holds significant potential for the development of cultural tourism, particularly in multiethnic contexts. The city of Prizren exemplifies this potential through its historical coexistence of Albanians, Turks, Bosniaks, Serbs, Roma, and other communities. This study explores the identification and mapping of cultural routes in such a multiethnic setting, emphasizing how shared heritage can contribute to sustainable tourism and intercultural understanding. The research methodology combines GIS mapping, field observations, interviews, spatial data analysis, and an in-depth examination of key cultural monuments. As Kosovo aspires to join the Council of Europe, which promotes cultural heritage through its Cultural Routes program, this research aims to support heritage preservation aligned with European values. It also contributes to Kosovo's broader European integration efforts and its engagement with transnational cultural initiatives.

KEYWORDS
cultural routes; heritage; multiethnic environment; Prizren; Kosovo

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1. Introduction

Cultural routes are a relatively new cultural phenomenon that contributes to the creation of new forms of cultural heritage (Majdoub 2010). According to Majdoub (2010), cultural routes are not only physical journeys through specific territories and local or national identities, but also mental journeys filled with values, meanings, and expectations – ultimately forming a tourist product. These routes vary in scale, ranging from local to intercontinental (Terzić and Bjeljac 2016), and often represent points of cultural encounter, emphasizing the contributions of different peoples and transmitting values such as solidarity, freedom, tolerance, and multiethnic integration (Genovese 2016). They reflect the historical interactions between people motivated by economic, religious, or cultural reasons and thus serve as a shared heritage of human history (Carreno 2003).

Cultural routes are more than physical paths; they represent symbolic values and often become tourist attractions in areas where they occur. As tourism products, they are subject to selective evaluation, aimed at attracting European and international interest (Cojocariu 2015). Their appeal is even greater in historically rich, multiethnic cities. They also have the potential to enhance cultural experiences by integrating heritage values, architectural types and functions, and historical periods (Balcan et al. 2024). Cultural heritage sites and buildings are assessed based on their unique values and tourism potential (Balcan et al. 2024).

Even countries with rich histories face challenges in attracting tourists. One effective strategy for promoting tourism is the creation of cultural routes, which support regional or national economic and tourist development (Božić and Tomić 2015). Cultural routes have also proven effective in fostering sustainable and inclusive tourism (Trono 2024). As complex cultural products, they can enrich national identity and elevate local heritage into globally recognized phenomena (Trono 2024).

The Council of Europe launched the Cultural Routes Program in 1980 to promote a shared European heritage. Some member states have integrated these routes into their cultural policies, while other countries, including Kosovo, aspire to join the Council and apply for this program. Kosovo, a small country in the central Balkans, has a rich history shaped by its diverse ethnic, religious, and cultural communities, all of which have influenced the country's identity and social cohesion.

Prizren, often referred to as the cultural capital of Kosovo, exemplifies this heritage. It is home to a wide range of ethnic and religious communities (Albanians, Turks, Bosniaks, Serbs, Roma, among others) and hosts a dense concentration of cultural monuments and religious sites linked to Muslim, Catholic, Orthodox, and Jewish traditions. Traditional crafts and historical coexistence further characterize the city. This study maps cultural routes in Prizren to highlight the city's rich heritage and address related challenges, while also supporting Kosovo's aspiration to join the Council of Europe.

The paper focuses on identifying key streets in Prizren that connect major historical and cultural sites. It also explores how these routes can promote cooperation among communities, not only within Prizren but across Kosovo. In doing so, the study highlights the potential of cultural routes to become important tourist destinations, strengthening livelihoods, and supporting the well-being of local residents of all backgrounds. The article contributes to discussions on cultural heritage preservation, multicultural coexistence, and sustainable tourism in multiethnic cities, offering insights relevant to other regions facing similar challenges. It also links cultural routes with broader European integration initiatives, giving the findings both local and international relevance.

2. Cultural Routes in European and Balkan context

The concept of cultural routes has received increasing attention in academic literature, with contributions from various disciplines. Cultural routes represent a distinctive product of creative tourism, connecting attractions and destinations across one or more countries. According to the Council of Europe, a cultural route is "a cultural, educational heritage and tourism cooperation project designed to develop and promote an itinerary or series of itineraries based on a historical route, cultural figure, concept, or phenomenon of transnational importance, contributing to the understanding and appreciation of shared European values" (Interreg Central Europe 2017). This concept is both complex and multidimensional.

Until 1990, the World Heritage Convention had not recognized the protection of cultural itineraries. In 1992, however, it became possible to designate linear areas as significant transportation and communication networks (Moulin and Boniface 2001). The concept gained further recognition in 1993, when the 'Routes of Saint James' (Camino de Santiago) was included on the World Heritage List (Genovese 2016). To reach international consensus, the International Committee on Cultural Routes (CIIC) was founded by ICOMOS members in 1998, followed by the publication of the ICOMOS Charter on Cultural Routes in 2008 (Lin et al. 2024). Since 2003, the category of 'cultural route' has also been included in the Operational Guidelines of the World Heritage Convention.

The ICOMOS Charter (2008) defines cultural routes as historical routes of human communication that served a specific and dynamic purpose. They are widely regarded as mechanisms for linking distant

places and people, preserving cultural heritage, and promoting sustainable tourism (Timothy 2018; Terzić 2014; Moulin and Boniface 2001). Sigley (2022) emphasizes the mobility of culture in the concept of "route heritage," noting that cultural expressions and exchanges evolve along historically constructed pathways. This emerging notion of route heritage is part of a broader reconsideration of what constitutes world heritage.

Berti (2015) argues that the term "route" should be understood not only in its physical sense but also as a network of natural and cultural sites linked by a common theme. Shishmanova (2015) adds that cultural routes offer a way to interpret history and culture together. Olsen et al. (2018) highlight the importance of mapping such routes to support the conservation and promotion of both tangible and intangible heritage.

Scholars have proposed different methodologies for identifying and mapping cultural routes. In multiethnic contexts, the process faces additional challenges due to varied interpretations of history, linguistic and religious differences, and past conflicts. Jansen-Verbeke (2007) explores the influence of cultural routes on tourism and local economic development. Graf (2012) emphasizes the importance of imagination and creativity in the use of cultural heritage for route development.

As of 2024, there are 48 Cultural Routes of the Council of Europe, covering a wide variety of themes that illustrate European memory, history, and heritage, and support the interpretation of Europe's present-day diversity. According to the Council of Europe (2025), the development of a cultural route requires the following steps:

1. Defining a theme that represents European values and is common to several countries.
2. Identifying heritage elements, including both tangible and intangible aspects.
3. Establishing a European network with legal status that includes at least three countries.
4. Coordinating shared activities in key thematic areas.
5. Establishing a unified visual identity to ensure recognition and coherence across Europe.

Cultural heritage reflects the shared past of a society, strengthens social solidarity, and maintains continuity by preserving accumulated experiences and traditions (Akyıldız and Olğun 2020). Cultural routes are closely linked to cultural tourism. They can unite well-known and lesser-known sites under a unifying theme, thereby improving visibility, promoting conservation, and strengthening heritage management. Tourists can engage with diverse heritage landscapes and gain a comprehensive experience of local history and culture while traveling along these routes (Gražulevičiūtė 2006).

In multiethnic environments, identifying and planning cultural routes is especially complex due to differing historical narratives and cultural priorities. These tensions can lead to disagreements over which sites or themes to emphasize. Nevertheless, cultural routes offer an opportunity to foster community engagement and a shared sense of belonging among diverse ethnic groups (Pattanaro and Pistocchi 2016). Integrating cultural heritage into tourism strategies also supports local economies and reinforces intercultural dialogue and cultural identity (Šćekić et al. 2022).

In addition to conceptual and political challenges, practical obstacles also exist. These include insufficient documentation, fragmented historical records, and regional disparities that complicate the definition of route boundaries. Other pressing concerns include preserving authenticity amid tourism development, managing urbanization and landscape change, and ensuring inclusive participation of local communities. Limited financial resources, legal constraints, and the need for cross-sectoral collaboration further complicate the process. Particularly in multiethnic areas, mapping cultural routes requires careful consideration of the cultural values of each group, attention to political sensitivities, and inclusive stakeholder engagement.

The identification of a Cultural Route must consider several key factors: its specific purpose and function; the tangible and intangible heritage it encompasses; the reciprocal cultural influences that shaped it; its structural form and historical-geographic context; whether its setting is urban or rural; its environmental characteristics; its relationship with the landscape; its duration over time; and its symbolic and spiritual dimensions. Together, these elements contribute to both the designation and deeper understanding of a route's significance (ICOMOS 2008).

More research is needed to assess how cultural routes contribute to social cohesion and sustainable development in ethnically diverse regions. Cultural routes represent one type of heritage network. These networks are rarely homogeneous and often consist of localized elements that make them inherently diverse. Even small localities can serve as important "nodes" in broader routes.

In this context, the city of Prizren, with its rich cultural heritage, emerges as a key node within potential cultural routes in Kosovo. Other towns such as Peja, Gjakova, and Prishtina may also be integrated into such networks. When connected through regional and international cooperation, these sites could form part of a transnational Balkan cultural route. This network might also include cities such as Skopje (North Macedonia), Tirana and Shkodra (Albania), and Sarajevo (Bosnia and Herzegovina). All of these cities, considered as nodes in this study, share similar heritage elements that reflect their layered historical, cultural, and religious identities.

3. Study area

Kosovo, the newest country in Europe, is located in the Western Balkans at the crossroads of civilizations. Throughout history, the region has been influenced by multiple cultural, religious, and political forces. It lies at the meeting point of Ancient Greek and Roman territories, served as a frontier of the Roman, Ottoman, and Austro-Hungarian empires, and is home to three major religious traditions: Islam, Orthodoxy, and Catholicism. This rich layering of civilizational influences has created a diverse cultural landscape that extends from the Illyrian period to the present (Regional Cooperation Council 2019; Ceko and Xhibo 2019).

Kosovo is a multiethnic society, home to Albanians, Serbs, Turks, Bosniaks, Roma, and other communities. Its cultural heritage is reflected in both tangible and intangible forms across many settlements. These features provide favorable conditions for the development of cultural routes. However, the field remains underexplored, with limited research and only a few projects currently underway (Krasniqi et al. 2021).

Within this context, the city of Prizren stands out as a leading candidate for the development of cultural routes. Located on the southern edge of the Dukagjini Plain at the foot of the Sharr Mountains, Prizren is a municipal and regional center whose territory borders Albania and North Macedonia. Its strategic location has historically enabled important

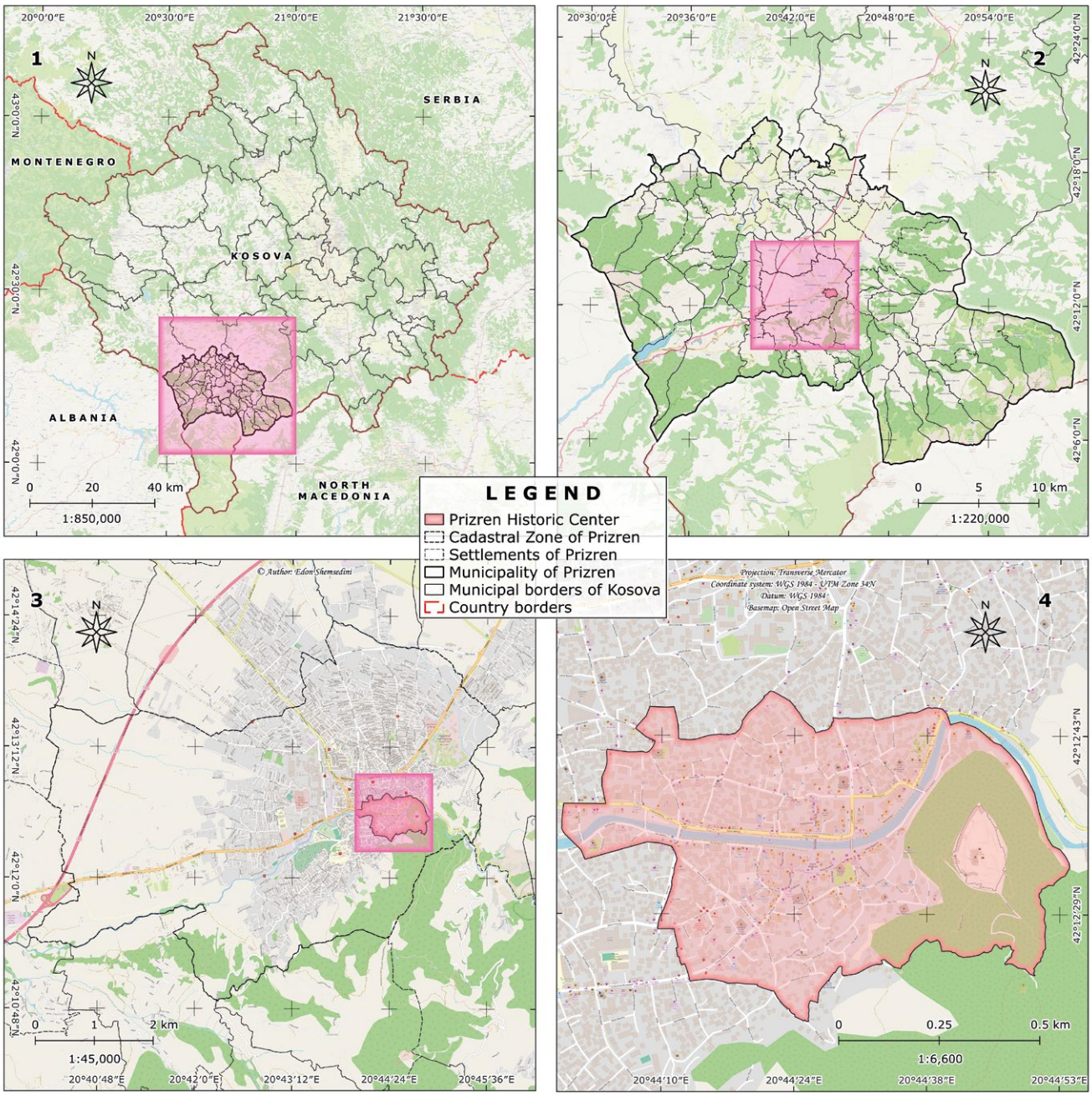

Fig. 2 Geographical location of Prizren.

communication links within Kosovo and with the wider region (KASA 2011, 2018).

Prizren is one of the oldest cities in the region and is considered among the earliest urban centers in Southeast Europe. Its Historic Centre, located at the intersection of ancient trade and travel routes, contains cultural and archaeological evidence from various eras and civilizations – including prehistoric settlements, the Dardanian civilization, and the Pre-Roman, Roman, Byzantine, Arbëror, Serbian, Ottoman, and Albanian periods (Bajçinovci and Thaçi 2016; Gülersoy 2022). Today, it remains a vibrant, living historic settlement characterized by distinctive vernacular and monumental architecture, fortifications, and engineering works, all integrated with the surrounding rivers and mountains (RROK 2020).

Fig. 1 illustrates the geographical location of the Municipality of Prizren, the Cadastral Zone of Prizren, and the Historic Centre. The Municipality spans approximately 626.98 km^2, the Cadastral Zone covers 29.31 km^2, and the Historic Centre encompasses about 0.63 km^2.

Prizren is widely recognized as a multiethnic and multireligious city, with Albanians, Turks, Bosniaks, and others contributing to its cultural diversity. Each group brings its own historical narratives and heritage values, which can make the design of unified cultural routes challenging. Competing interpretations of history or differing priorities over landmarks and figures may lead to disagreements about which elements should be emphasized.

Modern development poses additional risks. As Prizren continues to grow, heritage sites face pressure from commercialization and tourism-driven modifications, potentially threatening their authenticity. Balancing economic development with heritage preservation remains a central challenge. Moreover, the involvement of diverse stakeholders (ethnic communities, local governments, national institutions) adds complexity to consensus-building, as these groups often have competing interests.

Given Prizren's diverse population and layered history, the development of cultural routes must be approached with sensitivity to ensure that all communities are represented. Such an inclusive approach is essential for strengthening social cohesion. At the same time, urban expansion and infrastructure development continue to pose threats to existing heritage paths, particularly in older districts.

Although Kosovo is not yet a member of the Council of Europe, it holds significant potential to contribute to the Cultural Routes program. Prizren, as one of its most culturally rich and historically layered cities, presents a compelling case for such an initiative. Its heritage, shaped by centuries of coexistence and transformation, bridges past and present and offers a foundation for meaningful, sustainable cultural tourism (Municipality of Prizren 2012; Gülersoy 2022).

4. Materials and methods

The methodology used in this study offers a well-integrated approach for identifying and mapping cultural routes in the multiethnic city of Prizren. This research is based on the analysis of various relevant documents obtained from institutional and academic sources, as well as fieldwork conducted to identify and examine significant cultural sites.

The first step involved analyzing official documents and datasets to identify potential cultural routes based on their historical and cultural significance. Key sources included: Law No. 04/L-066 on the Historic Centre of Prizren (adopted by the Assembly of the Republic of Kosovo in 2012); Law No. 02/L-88 on Cultural Heritage; the Management Plan of the Historic Centre of Prizren; the List of Cultural Heritage for Temporary Protection of the Republic of Kosovo; the UNESCO Report on the Cultural Heritage of Kosovo; and other legal frameworks related to cultural heritage.

Following the document analysis, fieldwork was carried out to validate and supplement the initial findings. This included direct observations and semi-structured interviews with key stakeholders in the field of cultural heritage. Data collection focused on specific sites and areas identified as potential segments of future cultural routes.

The interviews were conducted using a semi-structured format to allow participants the freedom to elaborate beyond the core questions. Participants included teachers, government employees, officials from the Ministry of Culture and the Municipality of Prizren, heritage experts, and local residents. This purposive sample was selected based on the participants' expertise and depth of knowledge on the subject. All interviews were recorded and transcribed. The fieldwork, including interviews, was conducted during December 2024.

Geographic Information System (GIS) tools played a key role in the study by enabling the creation of interactive maps that visually represent the cultural diversity of the city. GIS helped identify spatial patterns and key areas of cultural significance, supporting the categorization and visualization of proposed routes.

The identified routes were categorized based on their function and cultural value:

- Historical routes connecting sites from different historical periods.
- Religious routes linking sacred sites of different faiths, reflecting multiethnic and multireligious coexistence.
- Contemporary routes associated with traditional urban practices such as local crafts, for which Prizren is well known.

The methodology also includes an assessment of the potential for each route to attract diverse groups

of tourists, with the aim of identifying opportunities for sustainable promotion and analyzing the prospective cultural and economic impacts.

Overall, this approach is designed not only to identify and promote cultural routes in Prizren but also to serve as a replicable model for other cities in Kosovo. Furthermore, it contributes to positioning Kosovo in alignment with the Council of Europe's Cultural Routes program, supporting its aspirations for European integration.

5. Results

The 2024 population census reaffirms Prizren's status as one of the most ethnically and religiously diverse cities in Kosovo (KAS 2024). This diversity is clearly reflected in its cultural sites, reinforcing the relevance of the proposed cultural routes. The presence of multiple ethnic communities has shaped the city's architectural forms, religious monuments, cultural traditions, and urban landscape. This pluralism enhances Prizren's appeal as a destination where visitors can engage with a unique blend of cultural influences.

According to the preliminary final results of the 2024 census conducted by the Kosovo Agency of Statistics, the Municipality of Prizren has a total population of 147,246, of whom 76,850 reside in the urban area of the city. The data presented in Tab. 1 and Tab. 2 show the ethnic and religious composition of the municipality, respectively.

The most valuable asset of Prizren lies in the cultural values inherited from past centuries. These are reflected in its distinctive architecture, unique urban structure, and enduring folk traditions. Prizren's cultural heritage is exceptionally diverse and represents one of the most compelling intersections of identities in Kosovo. The city has long served as a meeting point of different civilizations and cultures, whose collective contributions have shaped Prizren into a significant site of regional and global heritage value (Bajçinovci and Thaçi 2016; Gülersoy 2022). Known since antiquity, Prizren is often recognized as a unique urban center in the Balkans for its richness in cultural, civilizational, and religious heritage (Municipality of Prizren 2012).

To structure the analysis of Prizren's cultural landscape, two thematic routes were identified: the Religious Cultural Route and the Architectural Cultural Route. These routes highlight the city's multiethnic and multireligious character.

The data are presented graphically and in tabular forms. Fig. 2 is accompanied by Tab. 3 and Fig. 3 by Tab. 4, respectively. The figures contain maps in which the objects are presented with names and order numbers, as well as the hypothetical route between the objects. In the associated tables, the objects are also presented with names and order numbers as in the map, which indicates the period of construction, the status of whether it is under protection and what type of protection (permanent or temporary), the status reference number, the distances between the objects according to serial numbers and route, and the geographical coordinates. The routes in maps show just the paths that indicate the route according to a sequence of objects, but it is not necessary to be like this, but only a prefiguration to present the approximate distances between each other.

The Religious Cultural Route (Fig. 2) connects sacred sites from different faith traditions, including Islamic mosques, Orthodox and Catholic churches, and a Jewish cultural center. It illustrates Prizren's long-standing religious pluralism and the historical coexistence of its diverse communities.

The Architectural Cultural Route (Fig. 3) traces the city's urban and architectural evolution. It includes landmarks from various historical periods, such as the medieval Prizren Fortress and Kosovo's first hydroelectric plant, now repurposed as a museum. Together,

Tab. 1 Population by ethnicity in the Municipality of Prizren as of 2024.

Prizren Municipality – by ethnicity 2024		
Ethnicity	**Inhabitants**	**Percent (%)**
Albanian	114,484	77.75
Serb	202	0.14
Bosniak	18,379	12.48
Turk	9,819	6.67
Romani	2,101	1.43
Ashkali	1,260	0.86
Egyptian	117	0.08
Gorani	565	0.38
Others	235	0.16
Prefers not to answer	84	0.06
Total	**147,246**	**100%**

Source: Kosovo Agency of Statistics (KAS), 2024.

Tab. 2 Population by religion in the Municipality of Prizren as of 2024.

Prizren Municipality – by religion 2024		
Religion	**Inhabitants**	**Percent (%)**
Islam	142,321	96.65
Orthodox	206	0.14
Catholic	2,880	1.96
Others	438	0.30
No religious affiliation	400	0.27
Prefers not to answer	1,001	0.68
Total	**147,246**	**100%**

Source: Kosovo Agency of Statistics (KAS), 2024.

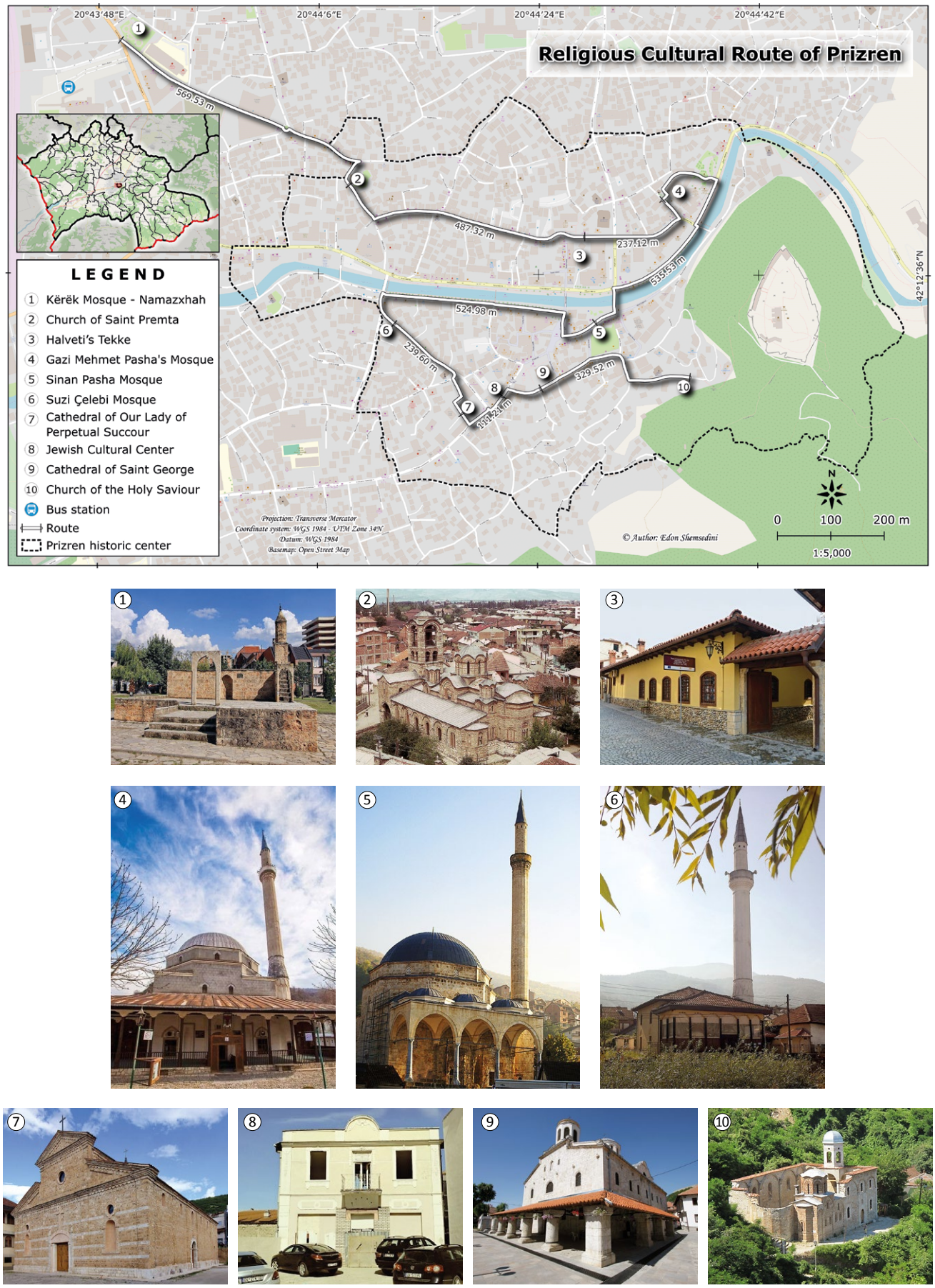

Fig. 2 Religious Cultural Route of Prizren.
Sources of images in Fig. 2: 1, 7 – Sh. Rexha; 2 – V. Vukotic; 3 – Ozoutback.com.au; 4 – B. Bytyçi; 5 – D. Spahiu; 6 – G. Behramaj; 8 – Reporteri.net; 9 – K. Novakovic; 10 – Panacomp.net.

Tab. 3 Sites of Religious Cultural Route.

N.	Name	Religion	Period	Status	Reference number	Distance by order	Coordinates
1	Kërëk Mosque – Namzxhah	Islam	1455	Permanent protection (Since 2023)	345	0.00 m	42°12'50.9"N, 20°43'51.23"E
2	Church of Saint Premta	Orthodox	Late Antiquity, Middle Ages	Permanent protection (Since 2016)	1974	569.53 m	42°12'41.8"N, 20°44'9.2"E
3	Halveti's Tekke	Tariqa (*part of a series on Islam*)	XIX Century	Temporary protection (06.10.2024–06.10.2025)	404	487.32 m	42°12'37.2"N, 20°44'27.33"E
4	Gazi Mehmet Pasha's Mosque	Islam	XVI Century	Permanent protection (Since 2024)	351	237.12 m	42°12'41.1"N, 20°44'35.44"E
5	Sinan Pasha Mosque	Islam	1594 (Middle Ages)	Permanent protection (Since 2023)	337	535.53 m	42°12'32.5"N, 20°44'28.96"E
6	Suzi Çelebi Mosque	Islam	1513	Temporary protection (06.10.2024–06.10.2025)	349	524.98 m	42°12'32.6"N, 20°44'11.54"E
7	Cathedral of Our Lady of Perpetual Succour	Catholic	XIX–XX Century	Permanent protection (Since 2023)	403	239.60 m	42°12'27.9"N, 20°44'18.27"E
8	Jewish Cultural Center	Jewish	XIX–XX Century	Temporary protection (06.10.2024–06.10.2025)	4758	111.21 m	42°12'29.1"N, 20°44'20.43"E
9	Cathedral of Saint George	Orthodox	XIX Century	Temporary protection (06.10.2024–06.10.2025)	2899	81.95 m	42°12'30.1"N, 20°44'24.39"E
10	Church of the Holy Saviour	Orthodox	Middle Ages	Temporary protection (06.10.2024–06.10.2025)	2855	329.52 m	42°12'29.2"N, 20°44'35.88"E

Source: Ministry of Culture, Youth and Sport of Republic of Kosovo.

these routes narrate Prizren's role as a cultural and historical crossroads in the Balkans.

Mapping and analyzing these routes revealed important aspects of accessibility, conservation, and tourism potential. Most sites are within a walkable distance, making them ideal for both guided and self-guided tours. The availability of historical and religious sites within close proximity enhances the

Tab. 4 Sites of Architectural Cultural Route.

N.	Name	Period	Status	Reference number	Distance by order	Coordinates
1	Upper City – Castle of Maidens	Middle Ages	Temporary protection (06.10.2024–06.10.2025)	2948	0 m	42°11'58.4"N, 20°45'42.89"E
2	Museum of Hydroelectricity	1926-28	Permanent protection (Since 2016)	1425	488.30 m	42°12'5.96"N, 20°45'42.91"E
3	Albanian League of Prizren	XIX Century	Permanent protection (Since 2023)	468	2437.57 m	42°12'41.2"N, 20°44'37.55"E
4	Hamam of Gazi Mehmet Pasha	1573–74	Permanent protection (Since 2016)	437	241.81 m	42°12'39.4"N, 20°44'29.33"E
5	Ethnological Museum – Shehzade's House	XIX Century	Permanent protection (Since 2023)	559	303.15 m	42°12'41.5"N, 20°44'21.37"E
6	Clock Tower – Archaeological Museum	XIX Century	Permanent protection (Since 2024)	438	346.27 m	42°12'40.6"N, 20°44'11.81"E
7	Beledije – Building of old Municipality	XIX Century	Permanent protection (Since 2024)	628	472.49 m	42°12'37.1"N, 20°44'6.67"E
8	Old Stone Bridge	Antiquity, Middle Ages	Temporary protection (06.10.2024–06.10.2025)	430	457.95 m	42°12'34.4"N, 20°44'26.21"E
9	Shatërvan Fountain	XIX Century	Temporary protection (06.10.2024–06.10.2025)	428	79.22 m	42°12'32.5"N, 20°44'25.93"E
10	Prizren Castle	Late Bronze Age, Late Antiquity, Middle Ages, till year 1912	Permanent protection (Since 2016)	1967	667.92 m	42°12'34.1"N, 20°44'44.01"E

Source: Ministry of Culture, Youth and Sport of Republic of Kosovo.

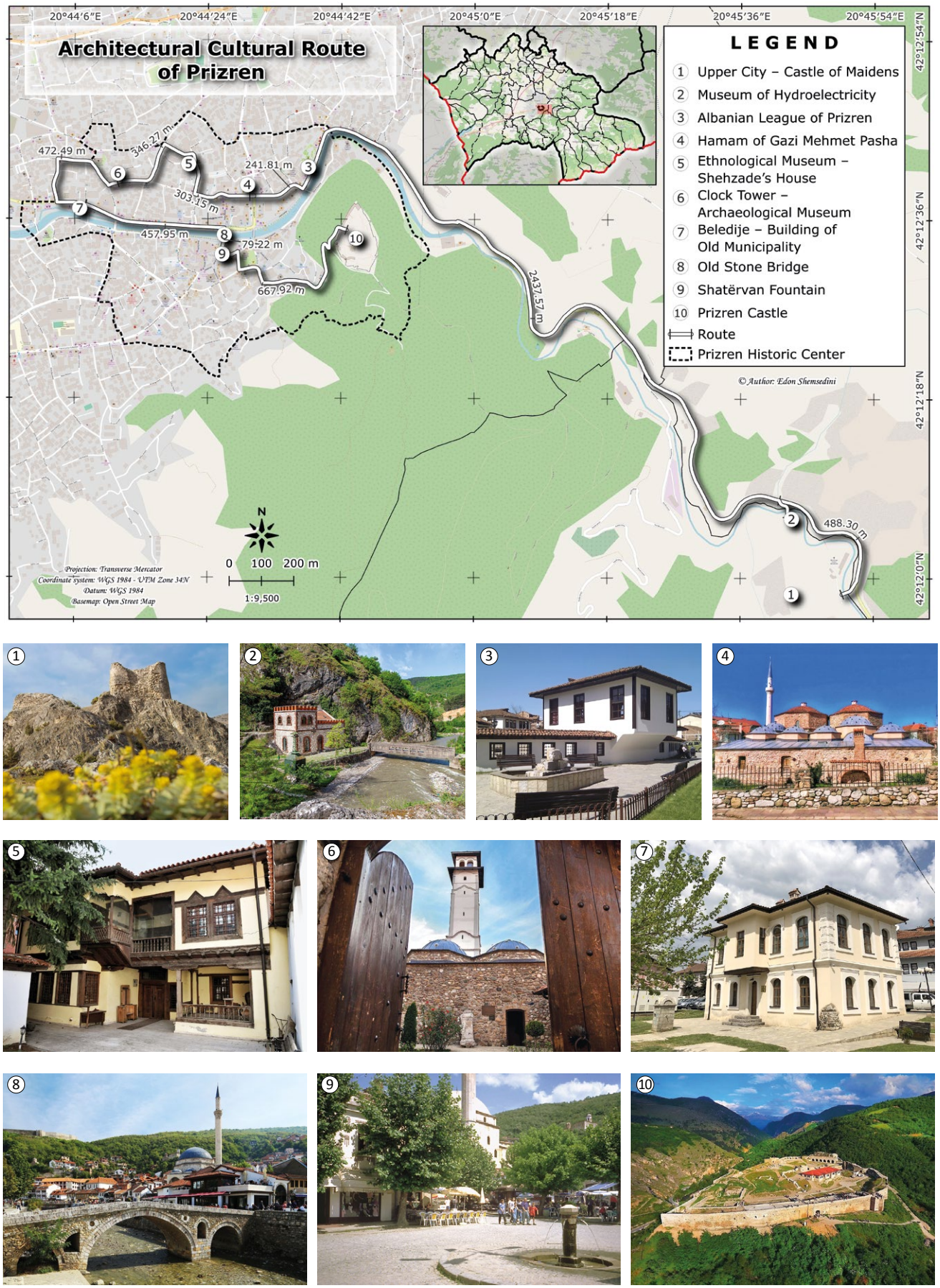

Fig. 3 Architectural Cultural Route of Prizren.
Sources of images in Fig. 3: 1 – L. Gashi; 2, 6 – Autostrada Biennale; 3, 7 – Koha.net; 4 – Cultural Bridge; 5 – Eduprizrenin.com; 8 – Trip Advisor; 9 – ObserverKult.com; 10 – Kosovosguide.wordpress.com.

appeal of cultural tourism in the city. Many of these monuments have permanent protection, as shown in Tab. 3 and Tab. 4, ensuring their preservation, but several remain under temporary protection, indicating the need for further conservation efforts. Integrating these routes into an official cultural heritage framework could facilitate access to funding for restoration projects and improve long-term heritage management. Despite the strong potential of these routes, challenges remain. Some cultural sites lack proper infrastructure, such as clear signage and visitor-friendly facilities. Promotion of these routes at the national and international levels is still limited, which means many foreign tourists are unaware of the historical wealth Prizren has to offer. Additionally, while the sites are protected by law, there is still a need for stronger institutional commitment to preservation, especially for monuments under temporary protection. Addressing these challenges would significantly enhance the visibility and sustainability of Prizren's cultural heritage.

The selection of monuments included in the Religious and Architectural Cultural Routes of Prizren was guided by several interrelated criteria, rooted in historical relevance, diversity of representation, accessibility, and their current legal protection status. These monuments were not chosen arbitrarily, but represent key landmarks that together reflect the multiethnic, multireligious, and multicultural identity of the city.

6. Discussion

By addressing cultural sites related to crafts, religious practices, and Ottoman heritage, this study contributes to forming a more inclusive and substantial narrative of cultural heritage in Prizren. It presents a systematic review of key national documents, such as the lists of cultural heritage under permanent and temporary protection, and relevant scholarly literature on cultural tourism and cultural routes.

Prizren, selected as the case study, is widely recognized as the historical and cultural capital not only of Kosovo but also of the Albanian population more broadly. However, to fully appreciate the significance of Prizren's heritage and its potential cultural routes, they must be understood within a broader historical and geopolitical context that includes Kosovo and the wider Balkans.

When identifying or applying the concept of cultural routes in any context, it is crucial to recognize their multidimensional value, including historical, cultural, and social dimensions. Cultural routes should not be treated merely as tourism products but as complex narratives shaped by memory, identity, and community. Each route must be understood within its specific context, and the active involvement of local communities is essential for preserving and interpreting its meaning.

Cultural routes can also be conceived as nodes within broader transnational heritage networks. Examples of such cooperation include initiatives like Via Dinarica or the Danube Wine Route. Given Prizren's proximity to the Sharr Mountains and its rich cultural heritage, the city could potentially be integrated into the Via Dinarica route. This would align Prizren with a growing pan-Balkan initiative that is increasingly popular among international tourists with diverse interests.

The findings of this research align with the Council of Europe's vision of cultural routes as tools for promoting coexistence, intercultural dialogue, and the shared values of modern European societies. By identifying and mapping cultural routes in Prizren, this study demonstrates how local heritage can embody and promote European social and cultural values.

Prizren should not be viewed as an isolated case but as a potential node in broader cultural networks of international relevance. Its inclusion in initiatives such as the Cultural Routes of the Council of Europe could serve as a platform for inclusive development. This development would involve all ethnic communities and leverage tourism to promote intercultural understanding and economic growth. These are important assets for Kosovo as it seeks deeper European integration and eventual membership in the Council of Europe.

As the paper has shown, Prizren's cultural landscape, highlighted through the Religious and Architectural Routes, illustrates how diverse civilizations, religions, and ethnic groups have collectively shaped the city's identity. The coexistence of mosques, churches, and a Jewish cultural center within a compact urban area is rare even by European standards. This strengthens Prizren's case for inclusion in transnational heritage networks. It also demonstrates that even in post-conflict contexts such as Kosovo, cultural heritage can serve as a foundation for unity, memory, and a forward-looking identity.

Prizren's story is not just about architecture or religion. It is about coexistence, plural memory, and the future of heritage in Southeastern Europe. The contribution of this study lies in its critical engagement with how heritage is interpreted, represented, and used in a multiethnic urban setting. Unlike much of the literature that focuses mainly on preservation or tourism development, this paper highlights the power dynamics embedded in heritage narratives. It asks who decides what is remembered, celebrated, or excluded.

These power dynamics are deeply relational, institutional, and symbolic. They reflect unequal relationships among state institutions, local authorities, cultural elites, and marginalized communities, each of whom exerts varying influence over heritage interpretation and management. By analyzing cultural routes in Prizren, this study reveals how heritage can either reinforce dominant historical narratives or

serve as a platform for inclusion and recognition of historically underrepresented groups.

In this sense, the paper challenges the romanticized notion of heritage as a neutral or unifying force. Instead, it argues for a more deliberate and inclusive approach to heritage curation, one that acknowledges complexity, diversity, and contested histories.

By focusing on Kosovo, a country with limited international visibility in heritage debates, this study brings attention to the overlooked richness of Balkan heritage and its role in global cultural networks. In contrast to scholarly discussions that are often centered on Western European contexts, this paper introduces a new perspective rooted in Southeastern Europe.

By referencing European initiatives such as the Council of Europe's Cultural Routes program, the ICOMOS Charters, and Via Dinarica, this work places Prizren and the Western Balkans within broader transnational heritage frameworks. This approach enhances the relevance of the study for scholars, practitioners, and institutions engaged in international heritage cooperation.

7. Conclusion

The findings of this study confirm that Prizren holds significant potential for inclusion in the Cultural Routes of the Council of Europe. Although the identified routes are not yet officially certified, they already function as informal heritage trails that attract both local and international visitors. Formal recognition would bring important benefits in terms of cultural heritage conservation, tourism development, and economic revitalization.

Official status would strengthen protection measures and enable access to funding for the restoration and maintenance of key sites. While many monuments in Prizren are already under some level of protection, the institutional support linked to formal cultural route designation would ensure more systematic and sustainable preservation for future generations.

A structured cultural route framework would also enhance the visitor experience. Clear itineraries, historical interpretation, and interactive storytelling (through signage, digital guides, and visitor centers) would make the routes more engaging and accessible. This would position Prizren more firmly as a cultural tourism destination in the Balkans and increase its visibility at both regional and international levels.

The economic and social benefits of well-managed cultural tourism are substantial. An increase in visitors would support local businesses such as accommodations, restaurants, and traditional craft vendors, generating employment and stimulating the local economy. Moreover, involving local communities in guided tours, heritage interpretation, and cultural events would foster a stronger sense of ownership and pride in the city's diverse history.

Integrating Prizren's routes into wider international heritage networks would open doors for cross-border cooperation with similar sites in Albania, North Macedonia, and Montenegro. Such regional collaboration could establish a shared cultural tourism circuit in the Western Balkans, strengthening Prizren's profile on the European cultural map.

Nonetheless, realizing this potential requires coordinated effort among municipal authorities, cultural institutions, and tourism stakeholders. Infrastructure improvements, targeted promotion, and stronger institutional backing will be necessary to sustain and scale the initiative. Digital promotion (such as interactive online maps, multilingual materials, and social media campaigns) can increase global awareness. Cultural festivals and events linked to the routes would further engage both residents and tourists.

With the right strategies and investments, Prizren's cultural routes can evolve from an academic proposal into a recognized and sustainable element of Europe's cultural heritage landscape. The city's unique combination of historical depth, architectural richness, and multiethnic tradition offers a compelling narrative. Integrating these routes into Kosovo's broader cultural heritage strategy would not only preserve Prizren's legacy but also create new opportunities for economic development and international cultural exchange.

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Impact of rapid urban growth on land use / land cover change and loss of urban green spaces: A comparative study of Guwahati city and Siliguri city, India

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ABSTRACT
This article analyzes the impact of the rapid growth of cities in India on their land-use and land-cover patterns. It is based on the case study of cities of Guwahati in the state of Assam and Siliguri in the state of West Bengal. Analyzing Census of India data between 1971 and 2011 and utilizing multi-temporal Landsat data from 1990 to 2020, the article employs GIS techniques, including the maximum likelihood algorithm for supervised classification, to generate comprehensive land use and land cover maps of these two cities. The normalized difference vegetation index (NDVI) method is additionally applied to discern changes in forest cover from 1990 to 2020. The analysis revealed rapid horizontal and vertical urban expansion of both Guwahati and Siliguri, accompanied by the conversion of forest and agricultural lands into built-up areas. The findings emphasize an urgent need for a robust policy framework to facilitate sustainable urban development and address the looming environmental challenges posed by the loss of green spaces in both cities and other urban regions of India.

KEYWORDS
urban growth; land use; NDVI; Guwahati City; Siliguri City; India

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1. Introduction

For the last few decades, there has been rapid growth and development of urban areas in most parts of the globe. It has become more so in many of the developing countries like India. Such a rapid growth of urban population in India has contributed to an increase in its urban population from 79 million to 388 million during 1961–2011 (Census of India 2011). This phenomenon of urban population growth in the country is mainly due to large-scale migration of people from rural and smaller towns to bigger cities in search of better employment opportunities and better quality of life (Bhat et al. 2017). Moreover, rapid urban population growth combined with unplanned development of urban areas in the country has been exerting tremendous pressure on its limited natural resources and land use and land cover (Sudhira et al. 2004). This type of rapid change in land cover often results in the loss of productive agricultural land, destruction of habitat, decline in the open green spaces, and loss of surface water bodies (Lopez et al. 2001; Alphan 2003; Swanwick et al. 2003; Kong and Nagagoshi 2006). Furthermore, the relentless expansion of urban areas stands as a primary driver behind deforestation, with urban green spaces emerging as a pivotal facet of urban ecosystems. These green havens not only furnish numerous environmental benefits but also serve as vital contributors to the overall well-being of city dwellers. Often regarded as the 'lungs' of urban environments, these green spaces play an indispensable role in upholding a city's sustainability by bolstering essential ecological functions that enhance both the natural and social fabric of urban landscapes. Regrettably, in recent decades, there has been an alarming depletion of urban green spaces, particularly in rapidly urbanizing developing nations like India (Siddique et al. 2020). This trend poses a grave threat to the ecological equilibrium of metropolitan areas, as substantial portions of tree cover, green spaces, and wetlands have been haphazardly transformed into built-up areas through unchecked processes of land use and land cover change, a trend that continues unabated. Accordingly, land use and land cover (LU/LC) changes predominantly caused by anthropogenic activities are one of the key components of local, regional, and global environmental change (Sala et al. 2000; Grimm et al. 2000; Lambin et al. 2003; Jensen 2005; Guan et al. 2011; Wu et al. 2013; Halmy et al. 2015). These human-induced land use and land cover changes also reflect the culmination of interaction between climate, ecosystem processes, biogeochemical cycles, and other biodiversity indicators (IGBP 1999).

The growth of cities is causing increasing stress on many aspects of the urban environment is reflected in many studies undertaken in recent times in different parts of the world. As a coping strategy sustainable development has been considered as a means of ensuring the human impacts within the capacity of the earth's environment (Trinder and Liu 2020). Moreover, a significant impact of land use change on green space loss and consequent environmental problems has been observed in Indian cities. A plethora of research has proved that urban growth resulting from land use and land cover change has adverse effects in the forms of biodiversity degradation, urban heat island formation, habitat fragmentation, drainage and water-logging problem, ground water depletion, micro-climate change, etc among many others (Griggs et al. 2014; de Souza et al. 2016; Son and Thanh 2017; Pawe and Saikia 2020). Thus, the insights obtained from understanding the dynamics of land use/land cover changes and their trajectories, including quantifying the extent of transformation in urban green spaces can help urban developers, planners, and policymakers for a healthy living environment in the urban areas. Moreover, this knowledge is essential for formulating effective planning strategies aimed at fostering the sustainable management of urban systems (Miller et al. 1998; Welch et al. 2002; Parmenter et al. 2003; Wang and Moskovits 2001; Manandhar et al. 2009; Zhang et al. 2017; Huang et al. 2018; Munthali et al. 2019; Parvez and Islam 2019; Abir and Saha 2021; Jahan et al. 2021; Shao et al. 2021).

With above background two growing cities of metropolitan character located in north-eastern region of India, namely Guwahati in Assam (Gateway to north-eastern region) and Siliguri in West Bengal (Gateway to Nepal, Bhutan, Bihar and Sikkim) are considered for comparative analysis of the pattern of urban growth and its impact on land use and land cover change and green space dynamics during the period 1990–2020. During the post-independence period, both cities have experienced a considerably high rate of population growth particularly due to the influx of people from the surrounding areas and other parts of the country, and also neighbouring countries of Bangladesh and Nepal. This phenomenon has greatly changed the demographic scenario of both cities in terms of population and associated characteristics within a short period. For example, Guwahati's city area expanded from 14.24 km^2 to 216.79 km^2 between 1961 and 1981, while Siliguri experienced growth from 15.54 km^2 to 41.90 km^2 from 1971 to 1991 (Census of India 1971 and 1991). The urban morphology of both cities and their outskirts has undergone marked changes, characterized by the unregulated growth of urban functions and infrastructure. Substantial portions of water bodies, agricultural lands, forested areas, and barren lands in the city periphery have been converted into residential and commercial zones (Hemani and Das 2016; Pawe and Saikia 2018; Sarkar and Chouhan 2019; Bhattacharjee et al. 2022). Furthermore, the once plentiful urban green spaces, crucial environmental assets comprising open areas primarily covered by vegetation, are facing rapid depletion and destruction at an alarming rate over the last few decades. Therefore, preserving

and sustaining these urban green spaces is imperative and necessitates a comprehensive public policy or city development plan. Such initiatives are crucial not only for the conservation of green spaces but also for enhancing the liveability and well-being of the urban communities in the study areas.

2. Study area

Looking at similarities in physical and socio-economic background, the growing cities of Guwahati and Siliguri have been selected for a comparative study. Guwahati, the largest city in North-East India, is located on the southern bank of the river Brahmaputra, bounded by Meghalaya hills on the south, Palasbari plain on the west, the Sila Grant reserved forest on the north, and the hills and plains of Chandrapur area on the east. Geographically, it is located at 26°5′N latitude and 91°51′E longitude and 193 feet above mean sea level with an area of 216.79 km^2. The city is situated on a flat plain interrupted by small hillocks rising up to a height of 300 m and a large number of wetlands and low-lying areas. It acts as a gateway to the north-east region for its locational advantages. The city experiences a humid sub- tropical climate characterized by the peak summer temperature rising to 38 °C, while in winter, it sometimes falls to 10 °C. The city receives an average annual rainfall of 200 cm. The total population of the city according to 2011 census stands at 9, 62,334 with a sex ratio of 931 females per 1000 males and population density of 4,393 persons/km^2. On the other hand, Siliguri city, which is one of the rapidly growing cities in West Bengal and sub-divisional headquarters of Darjeeling District and situated on the banks of river Mahananda and the foothills of the eastern Himalayan region. Geographically, it is located at 26°39′N latitude and 88°47′E longitude and 392 feet above mean sea level with an area of 41.90 km^2. The whole city area is very closely located from the countries of China, Bangladesh, Nepal, and Bhutan. Besides, the city forms the entry point to the north-eastern states, and as such it acts as a gateway to north-east India (Fig. 1). The city experiences a humid sub-tropical climate, being characterised by hot summers and dry winters. The average maximum temperature in summer and average minimum temperature in winter range between 38 °C and 15 °C. During the monsoon season (June to September) the city is lashed by heavy rains. The total population of the city according to the 2011 Census is 5, 13,264 with a population density of 12,249 persons/km^2. Its sex ratio stands at 946 females per 1,000 males.

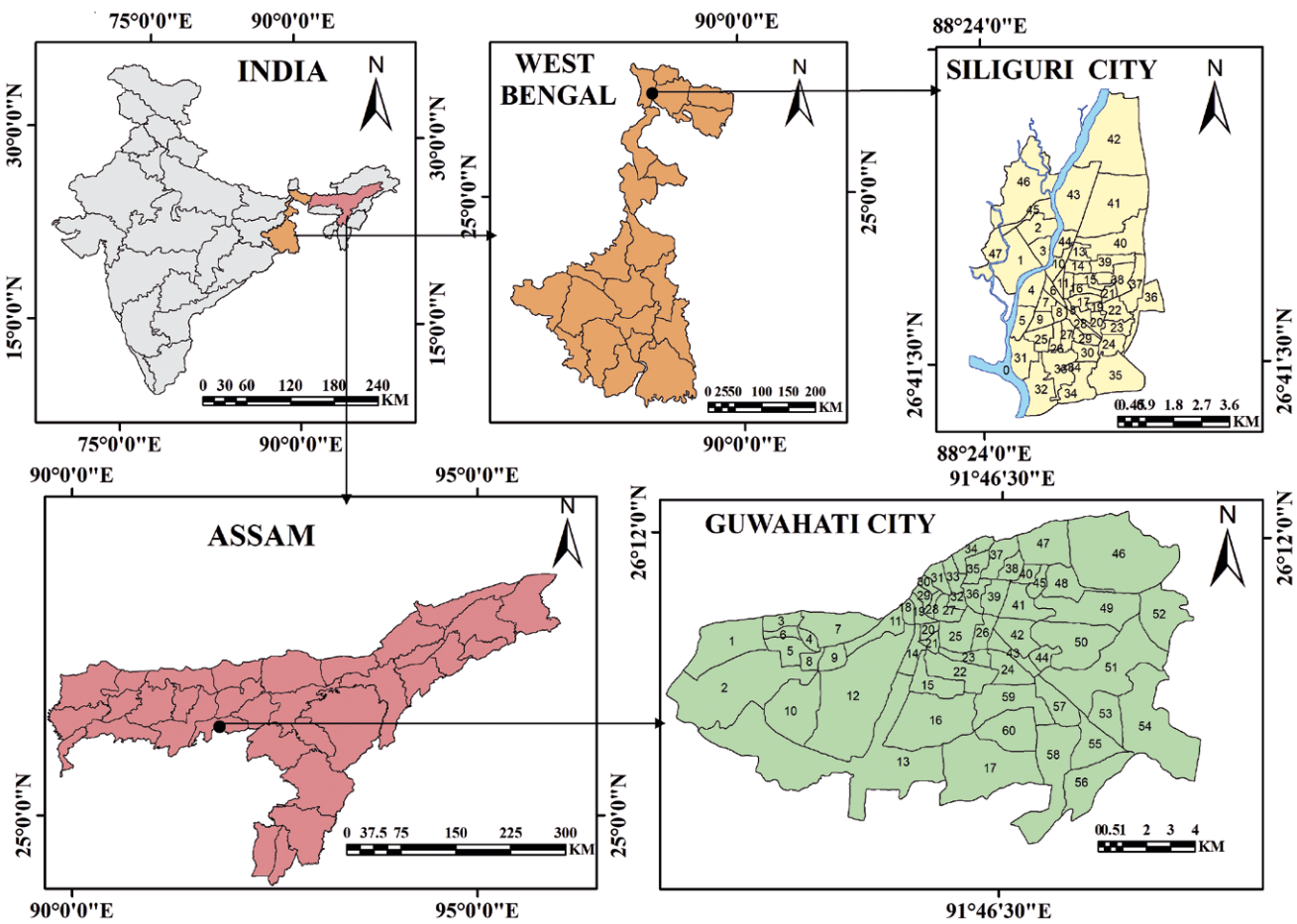


Fig. 1 Location map of the study area (Guwahati city and Siliguri city).

Tab. 1 List of Landsat data sets used in the study.

Satellite		Spatial Resolution (m)	Path/Row	Acquisition Date
Gawahati City	Landsat_5 TM	30	139/42	6/2/1990
	Landsat_5 TM	30	137/42	17/2/2005
	Landsat 8 OLI TIRS	30	137/42	11/2/2020
Siliguri city	Landsat_5 TM	30	139/42	6/2/1990
	Landsat_5 TM	30	139/42	15/2/2005
	Landsat 8 OLI TIRS	30	139/42	9/2/2020

Source: Landsat data collected from USGS Earth Explorer.

3. Materials and methods

The study is largely based on secondary data. The data related to population growth have been collected from Census of India publications for the period 1971–2011. Further, remote sensing data have been acquired from six cloud free Landsat images from the United States Geological Survey website. In order to fulfill the objective of comparing the two cities, all the images have been taken for same season of the year (Tab. 1). Accordingly, in order to understand the dynamics of urban growth pattern land use/land cover change analysis has been done and six land use maps have been prepared with the help of GIS environment (Fig. 2).

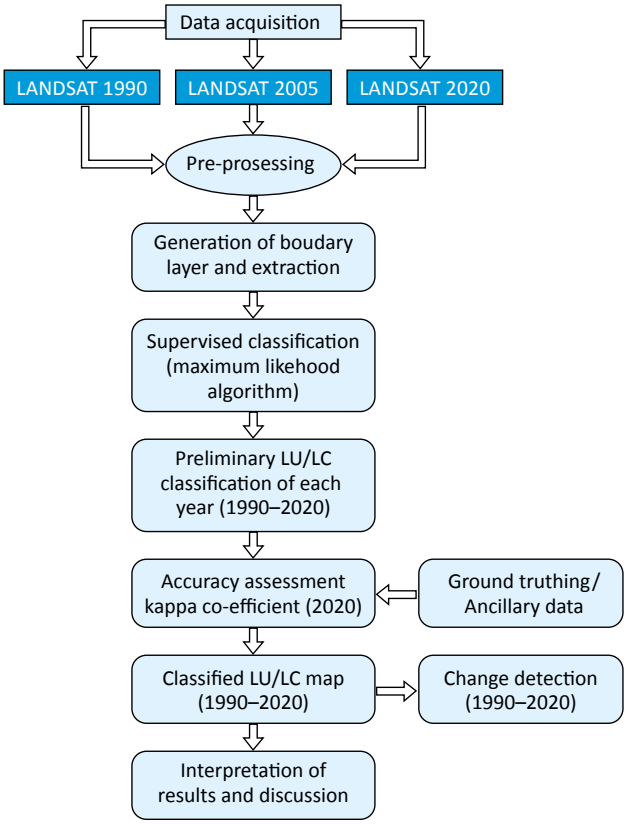


Fig. 2 Flow chart of the methodology of the study.

3.1 Image classification

Image clasification, which helps categorising an image into a smaller number of individual classess based on its spectral reflectance values (Jensen 2005), has been done through supervised classification technique by applying maximum likelihood algorithm. Hence, ground verification has been done by extensive GPS based field survey and ground control points of Google Earth pro software to get accuracy of result obtained for different land use categories. Furthermore, five land use classess like Agricultural land, Barren land, Forest, Built-up and Water body have been identified with the help of image interpretation elements and terrain characteristics of the study area (Tab. 2). Further, Sankey charts were also created using Python programming to illustrate the land use/land cover change matrix.

3.2 Accuracy assessment of the images

For validating the digitally classified images ground reference data were collected from google earth map and field visits with GPS. Accordingly, accuracy assessment was done for 2020 image and a total of

Tab. 2 LU/LC classification scheme used in the study.

LU/LC Classess	Description
Agricultural Land	All cultivated and uncultivated agricultural land areas such as farmlands, crop fields including fallow land.
Barren Land	Areas around and within forest protected areas with no or very little vegetation cover including exposed soils, rock, stone quarry, landfill sites and the areas of active excavation.
Forest	Decidous forest, mixed forest land, plantation, protected forest.
Built-up	Residential, commercial and services, industrial, socio-economic infrastructure and mixed urban and other urban, tranportation, road and railways.
Water Body	River, ponds, wetlands and reservoirs

Source: USGS Classification of land use and land cover, level-I.

Tab. 3 Confusion (error) matrix for 2020 LU/LC change map of Guwahati city.

Classified Image Categories	Agricultural Land	Barren Land	Forest	Built -up	Water Body	Row Total	User's Accuracy
Agricultural Land	41	0	2	2	0	45	91.00%
Barren Land	0	41	6	1	3	51	80.39%
Forest	4	0	45	2	1	52	86.54%
Built-up	2	0	0	43	3	48	89.58%
Water Body	7	4	1	0	42	54	77.77%
Colum Total	54	45	54	48	49	250	
Producer's Accuracy	75.93%	91.11%	83.33%	89.58%	85.71%		
Overall Accuracy			84.80%				
Kappa Co-efficient			0.68				

250 testing pixels were generated randomly. After-that, testing pixels were comapared with the classified map. Error matrix was applied to evaluate the user's and producer's accuracy and then compare the relationship between classified map data and reference data. Finally land use / land cover maps were produced with the help of user's accuracy, producer's accuracy, overall accuracy and Kappa coefficient (1, 2, 3, 4) The overall accuracy for 2020 classified maps of Guwahati city and Siliguri city are found to be 84.80% and 83.20% respectively. Hence, higher value of users accuracy in the land use class for Guwahati city is found in agricultural land and built-up area with 91.00% and 89.58% , the lower accuracy was occurred in the water body with 77.77% and and barren land with 80.39% (Tab. 3).

$$K = \frac{N\sum_{i=l}^{r} X_{ii} - \sum_{i=l}^{r}(X_i + * x_{+i})}{N^2 - \sum_{i=l}^{r}(X_i + * x_{+i})} \quad (1)$$

where K = Kappa coefficient of agreement,
N = Total number of observations (sample points),
X_{ii} = Diagonal; X_{+i} = Marginal row total (column i),
X_{i+} = Marginal row total (row i).

$$\text{Overall Accuracy} = \frac{\text{Number of Correctly Classified Pixels (diagonal)}}{\text{Total Diagonal of Reference Pixels}} \times 100 \quad (2)$$

$$\text{User's Accuracy} = \frac{\text{Number of Correctly Classified Pixels in Each Category}}{\text{Total Number of Reference Pixels in Each Category (Row Total)}} \times 100 \quad (3)$$

$$\text{Producer's Accuracy} = \frac{\text{Number of Correctly Classified Pixels in Each Category}}{\text{Total Number of Reference Pixels in Each Category (Column Total)}} \times 100 \quad (4)$$

On the other hand, the higher value of users accuracy in the land use class for Siliguri city is found in agricultural land with 86.67% and forest with 86.27% (Tab. 4). The lower accuracy is found in the case of water body with 77.78% and built-up land with 81.13% for the year 2020. Similarly Kappa coefficient is found to be 0.68 for Guwahati city and 0.64 for Siliguri city. Hence, Kappa coefficient method is used to assess how well the result of the remotely sensed classification matches with referenced data (Cohen 1960; Kar et al. 2018). Therefore, both the maps of the study area have been prepared with the minimum accuracy requirements to be used for the subsequent post-classification operation.

Tab. 4 Confusion (error) matrix for 2020 LU/LC change map of Siliguri city.

Classified Image Categories	Agricultural Land	Barren Land	Forest	Built -up	Water Body	Row Total	User's Accuracy
Agricultural Land	39	2	4	0	0	45	86.67%
Barren Land	2	40	0	0	5	47	85.10%
Forest	1	3	44	1	2	51	86.27%
Built-up	0	4	6	43	0	53	81.13%
Water Body	3	3	0	6	42	54	77.78%
Colum Total	45	52	54	50	49	250	
Producer's Accuracy	86.67%	76.92%	81.48%	86.00%	85.71%		
Overall Accuracy		83.20%					
Kappa Co-efficient		0.64					

3.3 Annual rate of change

The annual rates of change of LULC during three different periods (1991–2001, 2001–2015 and 1991–2015) have been calculated according to the procedure introduced by (Puyravad 2003; Teferi et al. 2013 and Batar et al. 2017) (5). This equation provides a benchmark for comparing LU/LC changes that are not sensitive to different periods during the study period.

$$r = \left(\frac{1}{t_1 - t_2}\right) \times ln\left(\frac{A_2}{A_1}\right) \quad (5)$$

where r is the annual rate of change for each class per year, A_2 and A_1 are the class areas (km^2) at time 2 and time 1 respectively and t is time (in year) interval between the two periods.

3.4 Gains and losses of LU/LC net change

Net change is the difference between the gain and loss (Teferi et al. 2013). The gains and losses of the land use and land cover during the study period have been derived from the cross tabulation for the year 1990, 2005 and 2020.

3.5 Calculation of Enhanced built-up and bareness index (EBBI)

The EBBI is a remote sensing index that applies bands of NIR, SWIR, and TIR. The NIR and SWIR bands are associated with a high contrast level for detecting built-up and bare land areas. In addition, in these bands, there is an inverse reflectance ratio with respect to detecting built-up or bare land areas (As-syakur et al. 2012).

$$\text{EBBI} = \frac{\text{SWIR} - \text{NIR}}{\sqrt[10]{(\text{SWIR} + \text{TIR})}} \quad (6)$$

3.6 Calculation of Normalized difference vegetation index (NDVI)

The calculation of NDVI is performed using the applied method of (Townshend and Justice 1986)

$$\text{NDVI} = \frac{(\text{NIR band} - \text{Rband})}{(\text{NIR band} + \text{Rband})} \quad (7)$$

where NIR means near infrared band and R means red band. For LANDSAT TM data band 3 and 4 and for LANDSAT OLI data band 4 and 5 were used to calculate NDVI. Hence, the NDVI value ranges from −1 to + 1. Values from 0 to +1 indicate vegetation cover. The values near to 0 indicate low vegetation cover and the values close to 1 indicate high density of vegetation.

4. Results

4.1 Pattern of population growth

The growth of population in terms of space and time is an important parameter to understand the pattern of urban growth, and the functional behaviour of people who live and work in the urban areas (Shanker 2001). So far the cities of Guwahati and Siliguri are concerned, both witnessed a phenomenal growth of population since the pre-independence period due to their geographically significant location and diverse functions. In the case of Guwahati city the population size has increased especially after shifting of the state capital from Shillong to Dispur (Guwahati) in 1972 with the establishment of new administrative centres, educational institutions, industries along with the expansion of trade and commerce (Begum 2010). This resulted in tremendous increase in population in the city during the last four decades (1971–2011).

Tab. 5 Trend of urban population growth in Guwahati city and Siliguri city (1971–2011).

	Year	Total Population	Decadal Growth Rate (in %)	Annual Growth Rate (in %)
Guwahati city	1971	1,23,783	–	–
	1981	Census not held		
	1991	5,84,342	372.07	8.06
	2001	8,09,895	38.60	3.32
	2011	9,62,334	18.82	1.74
Siliguri city	1971	97,484	48.90	–
	1981	1,54,378	58.36	4.70
	1991	2,16,950	40.53	3.46
	2001	4,72,374	117.73	8.09
	2011	5,13,264	8.66	0.83

* Census not held due to disturbation

Source: Census of India, 1971–2011, District Census Handbook, Kamrup District (Metro), Assam and Darjeeling District and Jalpaiguri District, West Bengal.

Its population has increased from as low as 1,23,783 in 1971 to as large as 9,62,334 in 2011 with annual growth rate ranges between 8.06% during 1971–1991 and 1.74% during the period 1991–2011 (Tab. 5). After the upgradation as city corporation in 1974, the municipal area of Guwahati increased from 14.24 km^2 in 1971 Census to 216.79 km^2 in 1991 Census with the inclusion of vast fringe areas within the city limit. At present, although the city area is witnessing a considerable decline in population growth rate, it had been as high as 372.07% during 1971–1991 as against the corresponding growth rate of 64.69% during 1991–2011.

On the other hand, Siliguri city experienced its population growth from as small as 97,484 in 1971 to as large as 5,13,264 in 2011, with the annual growth rate ranging between 8.09% during 1991–2001 and 0.83% the period 2001–2011. At the time of independence, a large number of refugees from the then East Pakistan (now Bangladesh) contributed to the rapid growth of population of Siliguri town, and in 1984 it was declared as a Class I town with a population of more than 1.5 lakhs. Till 1994 the Siliguri municipality had 30 wards with an area of 15.54 km^2. In the same year, after declaration of corporation status 17 new wards were added to the city and thereby its total area increased to 41.90 km^2. The Siliguri Municipal Corporation (SMC) spreads into the districts of Darjeeling and Jalpaiguri. At present, out of 47 wards of the SMC, 33 fall in Darjeeling district and the remaining 14 wards in the neighbouring district of Jalpaiguri (CDP 2015). It is worth mentioning that although Siliguri city has not experienced marked expansion in its area, its population size has increased at a rapid rate during the period 1971–2011 and the growth rate has always remained higher than the urban population growth rates of the district and state.

4.2 Land use / land cover change dynamics

The land use and land cover (LU/LC) pattern of an area is an outcome of the interplay of natural and socio-economic factors shaped by human activities over time and space (Mir and Ahmad 2014). The escalating global population and its surging demands for diverse activities have notably contributed to widespread land use and land cover changes on a worldwide scale (Seto and Kaufmann 2003; Kumar 2011). Notably, anthropogenic activities' impact on LU/LC changes stands as a fundamental driver of environmental transformations at local, regional and global scales (Munthali et al. 2019).

Against this backdrop, the study area encompassing Guwahati and Siliguri has undergone rapid land transformation over an extended period spanning from 1990 to 2020, propelled by mounting population pressure and the expansion of commercial and administrative functions in and around urban areas (Fig. 3). Throughout the study period, which spans from 1990 to 2020, agricultural land and forest areas remained predominant LU/LC classes in the region. In 1990, the total agricultural land area in Guwahati constituted 35.46% of the total area, a proportion that decreased to 33.55% in 2005. Similarly, the forest area decreased from 27.34% in 1990 to 26.66% in 2005. Concurrently, water bodies and barren land areas also experienced some decline in the proportion during the same period. In contrast, the built-up area in Guwahati accounting for only 5.27% in 1990 expanded significantly to 15.53% in 2005, and it became even more noticeable (32.38%) during 2005–2020 at the cost of considerable decline in the proportions of agricultural land, forests and barren land (Tab. 6, Fig. 3). But the long-term annual rate of change notably declined for agricultural land, forest, barren land and

Tab. 6 LU/LC change trend and annual rate of change in Guwahati city and Siliguri city.

LU/LC Categories	1990 (%)	2005 (%)	2020 (%)	Change			Annual Rate of Change		
				1990–2005	2005–2020	1990–2020	1990–2005	2005–2020	1990–2020
Guwahati City									
Agricultural Land	35.46	33.55	24.36	−1.91	−9.19	−11.1	−0.37	−2.13	−1.25
Barren Land	26.16	19.23	14.82	−6.93	−4.41	−11.34	−2.05	−1.74	−1.90
Forest	27.34	26.66	23.31	−0.68	−3.35	−4.03	−0.17	−0.90	−0.53
Built-up	5.27	15.53	32.38	+10.26	+16.85	+27.11	+7.20	+4.90	+6.05
Water Body	5.77	5.04	5.13	−0.73	+0.09	−0.64	−0.90	+0.11	−0.39
Siliguri City									
Agricultural Land	31.04	28.40	19.53	−2.64	−8.87	−11.51	−0.63	−2.46	−1.54
Barren Land	25.51	17.89	12.32	−7.62	−5.57	−13.19	−2.40	−2.44	−2.43
Forest	20.14	10.50	4.24	−9.64	−6.26	−15.9	−4.38	−6.00	−5.19
Built-up	13.43	37.38	56.31	+23.95	+18.93	+42.88	+6.79	+2.77	+4.78
Water Body	9.88	5.83	7.60	−4.05	+1.77	−2.28	−3.56	+1.81	−0.87

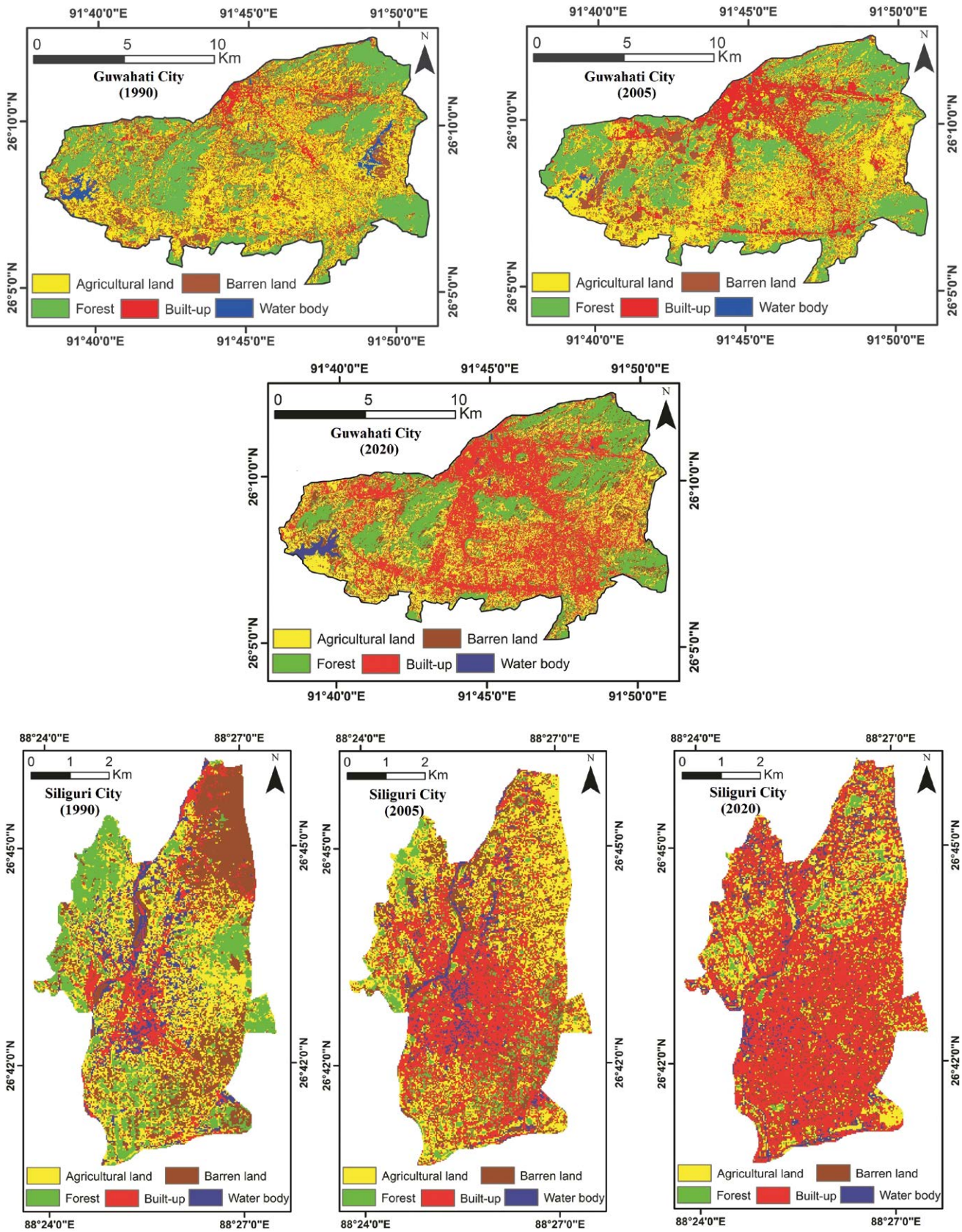


Fig. 3 Trends in land use / land cover change in Guwahati city and Siliguri city (1990–2020).

water body areas. Conversely, the built-up area experienced an overall increase in annual rates of change during 1990–2020. In the Siliguri city area, the land use transformation has been quite distinct. In 1990, the built-up area constituted 13.43% of the total area, which rose to 37.38% in 2005 (Fig. 3). During this period the proportion of agricultural land, barren land, forest, and water body decreased significantly.

Remarkably, during the subsequent period of 2005–2020, Siliguri city experienced significant land use transformation further expansion of built-up area, underscoring the dynamic nature of urban growth and its associated environmental implications.

In the year 2020, the built-up area covered a large expanse of Siliguri city (56.31%) (Fig. 3). Concurrently, agricultural land, barren land, and forest areas witnessed a marked reduction during 2005–2020. On the other hand, expansion of area under water body to the extent of 7.60% is attributed to the reclamation of dying waterbodies and their better management during that period (Hoque and Rohatgi 2022). Agricultural land, forest, barren land, and water body areas exhibited considerable decline during 1990–2020. In contrast, the built-up area experienced an overall increase in annual rates of change from 6.79% km^2 to 4.78% km^2 over the same period. This data suggests a trend of increasing built-up areas during 2005-2020, which indicates that both the cities have undergone haphazard growth and sprawl due to unplanned and uncontrolled development of various infrastructural setups. Consequently, this has led to a drastic change in the previous land-use system.

4.3 Gain and loss of land use and land cover (net change)

The comprehensive analysis of net change in terms of gains and losses for each LU/LC classes for Guwahati city and Siliguri city during the periods 1990–2005, 2005–2020 and 1990-2020 are depicted in (Tab. 7). In the context of Guwahati city, the data reveals noteworthy transformations in LU/LC during 1990–2020. It is observed that there had been substantial loss of area under barren land (12.82 km^2), followed by agricultural land (3.53 km^2), forest (1.25 km^2) and water bodies (1.35 km^2) during 1990-2005. Again, between 2005 and 2020, agricultural land experienced the highest loss of 16.99 km^2, followed by barren land (8.16 km^2), forest (6.21 km^2) and water bodies (0.16 km^2). Over the entire period from 1990 to 2020, agricultural land and barren land witnessed the most significant loss to the extent of 20.52 km^2 and 20.98 km^2 respectively, followed by forest cover (7.46 km^2) and water bodies (1.19 km^2). This has been largely due to rapid expansion of area under built-up category through addition of 18.97 km^2 during 1990-2005 and 31.16 km^2 during 2005–2020.

So far Siliguri city is concerned, during the period of 1990–2005, a considerable loss of barren land occurred (8.97 km^2), followed by agricultural land (2.92 km^2), forest cover (3.66 km^2) and water bodies (1.54 km^2). Contrarily, there was a gain of 1.06 km^2 in built-up area during the same time frame. Later, during 2005–2020, the highest loss in barren land was observed (7.23 km^2), followed by forest cover (2.34 km^2), agricultural land (2.06 km^2) and water bodies (0.68 km^2). Conversely, there has been expansion of built-up area totalling 4.35 km^2 during 1990–2020 following addition 1.06 km^2 during 1990–2005 and 3.29 km^2 during 2005–2020.

4.4 Change detection analysis of LU/LC of Guwahati city and Siliguri city (1990–2020)

Change detection describes and quantifies the transformations associated with LU/LC changes in the landscape using geo-referenced multi-temporal remote sensing data acquired for the same geographical area between the considered acquisition dates (Ramachandra and Kumar 2004). In the context of change detection analysis conducted in Guwahati and Siliguri cities, the findings underscore significant land use and land cover (LU/LC) transformations over a period of three decades (1990–2020). The results indicate a notable increase in built-up areas during this time frame, driven by the growing urban population and ongoing infrastructure developments in and around both cities. Between 1990 and 2005, Guwahati

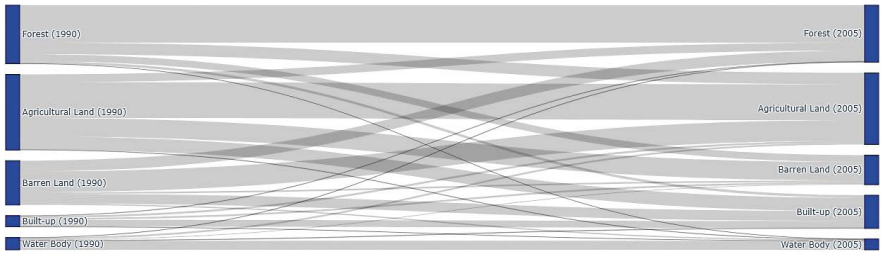
Tab. 7 Net change of LU/LC categories of Guwahati city and Siliguri city.

	LU/LC Categories	Net Change (Gain-Loss) (in km^2)		
		First period (1990–2005)	Seccond period (2005–2020)	Third period (1990–2020)
Guwahati City	Agricultural Land	−3.53	−16.99	−20.52
	Barren Land	−12.82	−8.16	−20.98
	Forest	−1.25	−6.21	−7.46
	Built-up	18.97	31.16	50.13
	Water Body	−1.35	0.16	−1.19
Siliguri City	Agricultural Land	−2.92	−2.06	−4.98
	Barren Land	−8.97	−7.23	−16.20
	Forest	−3.66	−2.34	−6.00
	Built-up	1.06	3.29	4.35
	Water Body	−1.54	0.68	−0.86

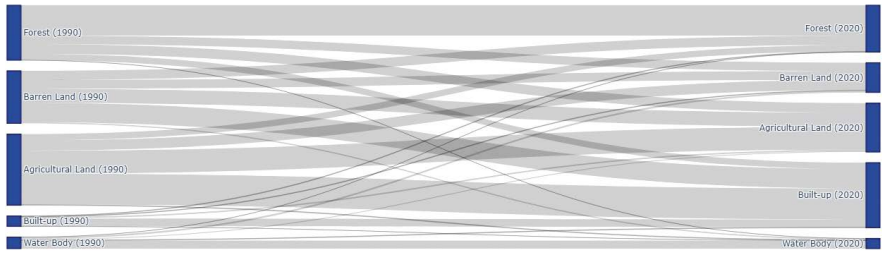
Tab. 8 Land use / land cover change matrix of Guwahati city during (1990–2020).

1990–2005 (in km²)	Forest	Barren Land	Agricultural Land	Water Body	Built-up
Forest	32.35	5.98	10.02	0.06	2.15
Barren Land	9.36	1.40	17.94	1.03	8.65
Agricultural Land	6.88	15.93	30.89	0.36	11.50
Water Body	0.29	0.66	1.48	7.77	0.45
Built-up	0.41	1.57	1.70	0.08	5.96
2005–2020 (in km²)	**Forest**	**Barren Land**	**Agricultural Land**	**Water Body**	**Built-up**
Forest	28.95	7.25	8.18	0.34	4.57
Barren Land	5.47	6.12	10.02	0.53	13.41
Agricultural Land	5.86	11.19	22.73	1.15	21.11
Water Body	0.13	1.35	0.52	7.04	0.28
Built-up	2.67	1.48	3.61	0.42	20.54
1990–2020 (in km²)	**Forest**	**Barren Land**	**Agricultural Land**	**Water Body**	**Built-up**
Forest	27.96	7.73	8.84	0.10	5.93
Barren Land	8.47	8.08	12.92	1.15	17.75
Agricultural Land	5.94	9.42	21.09	0.63	28.49
Water Body	0.15	1.62	0.91	7.43	0.54
Built-up	0.57	0.55	1.28	0.16	7.18

LU/LC Class-wise Transition Sankey Diagram of Guwahati City (1990–2005)



LU/LC Class-wise Transition Sankey Diagram of Guwahati City (2005–2020)



LU/LC Class-wise Transition Sankey Diagram of Guwahati City (1990–2020)

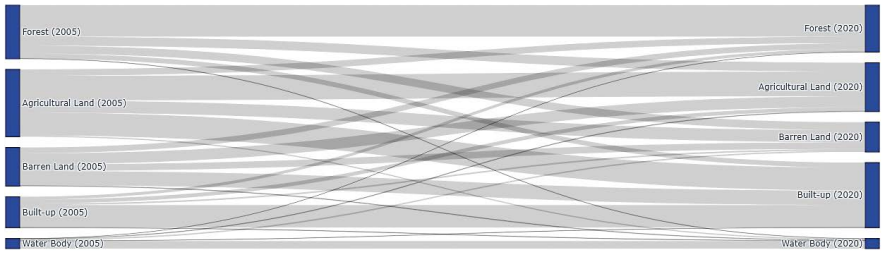


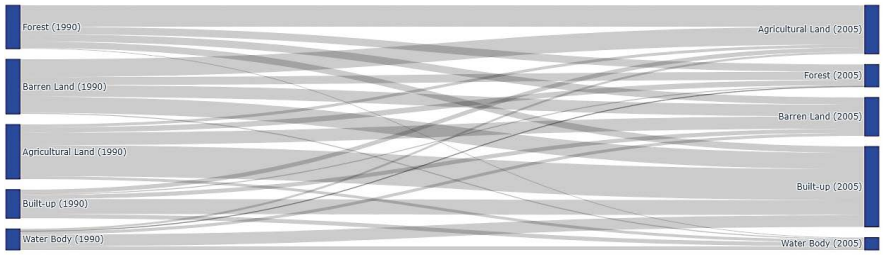
Fig. 4 Land use / land cover change transitions of Guwahati city (1990–2020).

city witnessed the conversion of 2.15 km² of forest area, 8.65 km² of barren land, 11.50 km² of agricultural land, and 0.45 km² of water body area to built-up areas. Conversely, only 0.41 km² of built-up area got converted to forest, 1.57 km² to barren land and 1.70 km² to agricultural land during the same period. During 2005–2020, the highest transitions occurred in the agricultural land and barren land getting converted to built-up area (Tab. 8, Fig. 4). When the entire period of 1990–2020 is taken into consideration, agricultural and barren lands experienced the most significant transitions with 44.48 km² and 40.29 km²

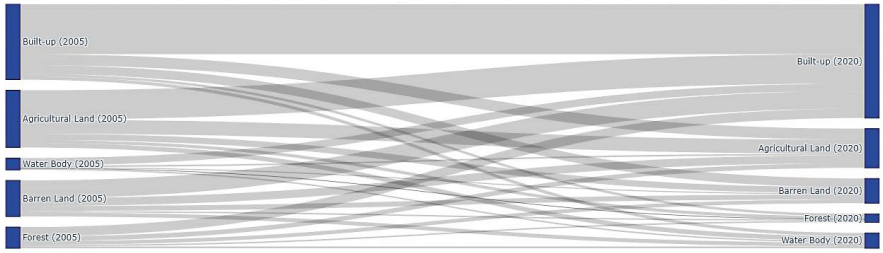
Tab. 9 Land use / land cover change matrix of Siliguri city during (1990–2020).

1990–2005 (in km²)	Forest	Barren Land	Agricultural Land	Water Body	Built-up
Forest	1.31	1.27	3.71	0.15	1.12
Barren Land	1.37	2.02	3.12	0.20	2.82
Agricultural Land	0.95	2.17	0.49	0.49	5.41
Water Body	0.11	0.53	0.37	0.63	2.04
Built-up	0.18	0.71	0.76	0.70	2.64
2005–2020 (in km²)	**Forest**	**Barren Land**	**Agricultural Land**	**Water Body**	**Built-up**
Forest	0.29	0.69	0.86	0.33	1.77
Barren Land	0.26	0.94	1.47	0.75	3.29
Agricultural Land	0.54	1.15	2.62	0.88	5.48
Water Body	0.02	0.20	0.31	0.29	1.36
Built-up	0.47	1.64	2.04	0.60	9.28
1990–2020 (in km²)	**Forest**	**Barren Land**	**Agricultural Land**	**Water Body**	**Built-up**
Forest	0.18	0.94	1.44	0.63	4.40
Barren Land	0.74	1.32	2.49	0.68	4.41
Agricultural Land	0.40	1.46	1.95	0.75	7.14
Water Body	0.07	0.37	0.58	0.42	2.27
Built-up	0.19	0.54	0.89	0.38	3.03

LU/LC Class-wise Transition Sankey Diagram of Siliguri City (1990–2005)



LU/LC Class-wise Transition Sankey Diagram of Siliguri City (2005–2020)



LU/LC Class-wise Transition Sankey Diagram of Siliguri City (1990–2020)

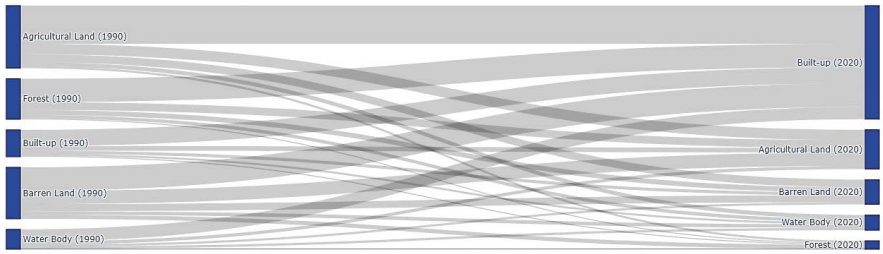


Fig. 5 Land use / land cover change transitions of Siliguri city (1990–2020).

respectively getting converted to other classes. The post-classification comparison reveals that 28.49 km² of agricultural land in 1990 transformed into built-up area by 2020, while 17.75 km² of barren land in 1990 converted to built-up land in 2020. Similarly, 5.93 km² of forest area and 0.54 km² of water bodies in 1990 changed to built-up land in 2020 in Guwahati city.

So far the nature and dimension of LU/LC transformation in Siliguri city is concerned, 1.12 km² of forest area, 2.82 km² of barren land and 5.41 km² of agricultural land got converted to built-up areas as against

only 0.18 km^2 of built-up area transformed into forest, 0.71 km^2 into barren land, 0.76 km^2 into agricultural land and 0.70 km^2 into water bodies during the period 1990-2005 (Tab.9, Fig. 5). Between 2005 and 2020, agricultural land experienced the highest transition, with 5.48 km^2 of its total area in 2020, primarily converting to barren land (3.29 km^2), forest (1.77 km^2) and water bodies (1.36 km^2) transforming into built-up areas. During the entire period of study (1990–2020), agricultural, barren, and forest lands experienced substantial transitions with 9.75 km^2, 8.32 km^2, and 7.41 km^2 respectively being converted to other classes. The post-classification comparison reflects that 7.14 km^2 of agricultural land in 1990 transformed into built-up areas by 2020, while only 0.89 km^2 of built-up area converted to agricultural land. Similarly, 4.41 km^2 of barren land in 1990 converted to built-up land in 2020, while only 0.54 km^2 of built-up land transformed to barren land. Additionally, 4.40 km^2 of forest area in 1990 was converted to built-up land in 2020, with only 0.19 km^2 of built-up land transforming into forest area during the same period. Furthermore, 2.27 km^2 of water bodies in 1990 were converted to built-up land in 2020. This relentless conversion of agricultural, barren, and forest lands to built-up areas has exerted immense pressure on the already limited natural resources, posing a threat to ecological balance and giving rise to various environmental challenges in and around the cities.

Although both cities have expanded in all directions, the prominent growth areas have been observed in the north-western, eastern, and southern parts of Guwahati and the southern and south-eastern parts of Siliguri (Fig. 6). This spatial pattern underscores the visible alteration of LU/LC classes due to the rapid urban growth experienced by both cities. While Guwahati exhibits a higher growth rate than Siliguri, both cities manifest similar urban growth patterns and land use changes. Guwahati's accelerated expansion is reflected in the substantial increase in built-up areas, indicating widespread clearing of forests, agricultural lands, and encroachment into barren and wetland areas for commercial and residential purposes. Similarly, Siliguri has witnessed a rapid transformation through the conversion of forested areas, agricultural lands, barren lands, and water bodies into built-up areas.

4.5 Spatio-temporal analysis of EBBI

The Enhanced Built-up and Bareness Index (EBBI) is a technique based on remote sensing data to classify and map the extent of built-up areas and barren land. It basically helps to differentiate between the urbanized (built-up) areas and barren areas lacking vegetation. The EBBI is a remote sensing index that applies wavelengths of 0.83 µm, 1.65 µm, and 11.45 µm, (NIR, SWIR, and TIR, respectively) to Landsat ETM+ images. These wavelengths are selected based on the contrast reflection range and absorption in built-up and bare land areas. Therefore, the reflectance values of built-up areas are higher due to the longer sensor wavelengths. The NIR wavelength, which corresponds to band 4 in Landsat ETM+ and band 5 in SWIR, is associated with a high contrast level for detecting built-up and bare land areas (Fig. 7). The TIR can distinguish high and low levels of albedo in built-up objects. Moreover, the utilisation of TIR band is very effective for mapping built-up areas based on a low albedo, which eliminates the effect of shadows and water, while a high albedo demonstrates built-up and bare land areas clearly (Weng 2008). Therefore, the study presents the Enhanced Built-up and Bareness Index (EBBI) values for the years 1990, 2005, and 2020 in Guwahati and Siliguri cities. The built-up area of Guwahati city in 1990 was 45 km^2. Over the following 15 years (1990–2005) this area increased to 83 km^2 reflecting a growth rate of 47.33% during the period. The built-up area further expanded from 83 km^2 to 100 km2 by experiencing an increase of 57.05% puring the period 2005–2020. This increase in built-up area over time highlights the process of rapid urbanization of the city. In contrast, the bare land area in Guwahati city evidenced a significant decrease over the period. In 1990, the total bare land area was 118.08 km^2, and by 2005 it had reduced to 86.92 km^2 by showing a decrease of 26.29% and further declined to 57.47 km^2 by 2020 reflecting a decrease of 34.15% This reduction

Fig. 6 Field photo of built-up areas, (A) Guwahati city, (B) Siliguri city.

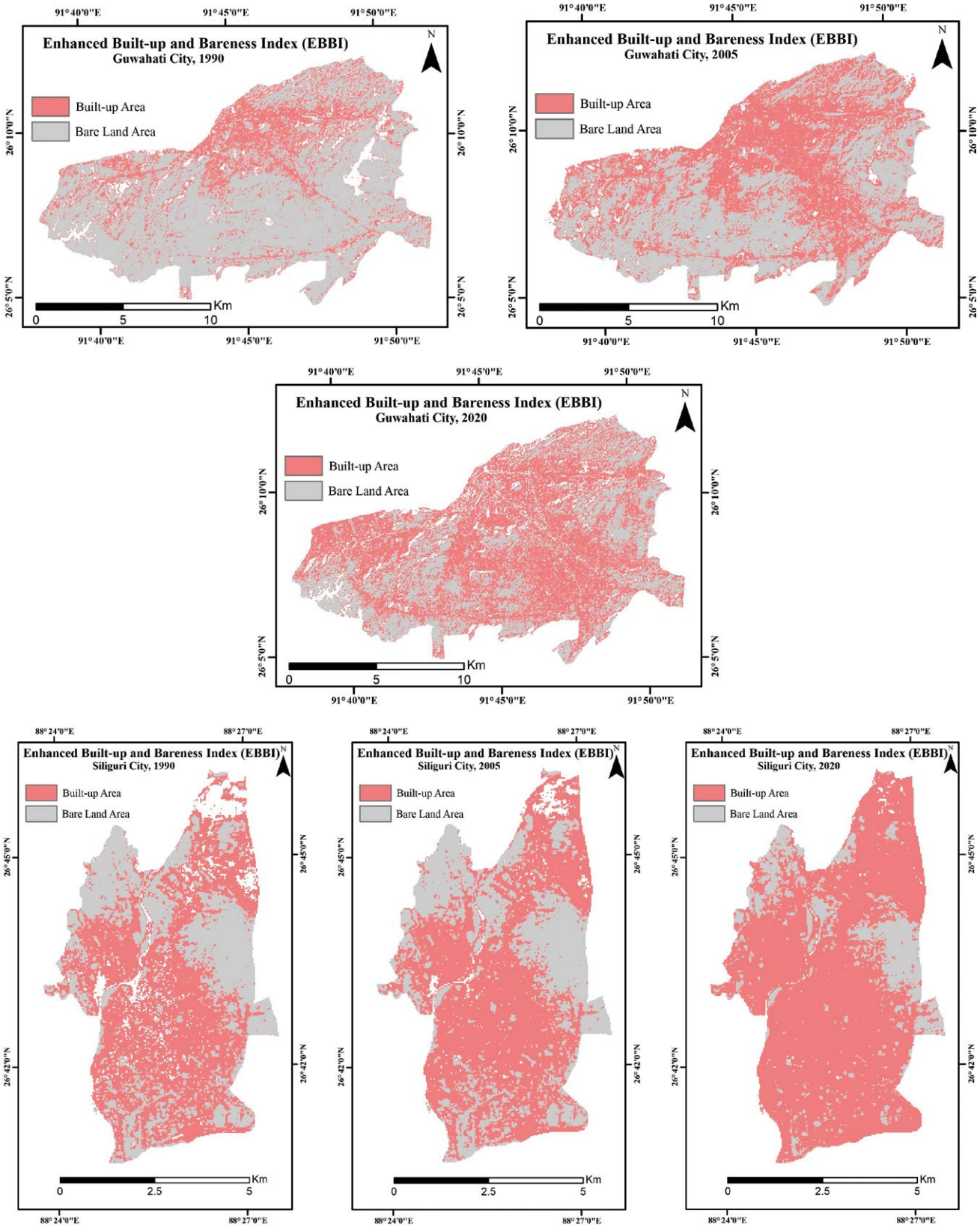


Fig. 7 Changing pattern of Enhanced built-up and bareness index (EBBI) in Guwahati City and Siliguri City (1990–2020).

in bare land is observed at a rate of 66.08% during 1990–2005 and 32.55% during 2005–2020. The decreasing area of bare land corresponds to the expansion of built-up areas indicating a growing trend of land conversion for urban development.

So far Siliguri city is concerned, the total built-up area in 1990 was 20.87 km^2, which increased to 22.79 km^2 in 2005, and further expanded to 30.92 km^2 by 2020. Accordingly, the proportion of built-up areas in the city, which was 55.24% in 1990, rose to 60.38%

Tab. 10 The percentage of built-up area and bare land area of EBBI in Guwahati city and Siliguri city (1990–2020).

Year	Guwahati City				Siliguri City			
	Built-up Areas (in km²)	Increasing Rate of Built-up Areas (in %)	Bare Land Areas (in km²)	Decreasing Rate of Bare Land Areas (in %)	Built-up Areas (in km²)	Increasing Rate of Built-up Areas (in %)	Bare Land Areas (in km²)	Decreasing Rate of Bare Land Areas (in %)
1990	45.00	26.02	118.08	66.88	20.87	55.24	15.89	42.03
2005	83.00	47.33	86.92	49.23	22.79	60.38	13.87	36.78
2020	100.00	57.05	57.47	32.55	30.92	81.83	6.63	17.55

in 2005 and 81.83% in 2020. This type of steady growth of built-up area indicates the rapid urban development over three decades. In contrast, the total barren land area in the city was 15.89 km² in 1990, which decreased to 13.87 km² in 2005 and further reduced to 6.63 km² in 2020. Similarly, its proportion in the city also decreased over time, from 42.03% in 1990 to 36.78% in 2005 and finally to 17.55% in 2020. This decline in barren land can be attributed to the city's urban expansion, as more areas have been developed for residential, commercial, and infrastructural purposes by converting the unused barren land. When compared between the cities of Guwahati and Siliguri, the degree of transformation into built-up area is higher in Guwahati (122%) than that in Siliguri (48%) (Tab. 10).

4.6 Spatio-temporal analysis of NDVI

The study presents the Normalized Difference Vegetation Index (NDVI) values for the years 1990, 2005, and 2020 in Guwahati and Siliguri cities, categorized into different ranges of NDVI. The NDVI represents the coverage and health of vegetation in an area. The NDVI of a Landsat image is generated from the red and near-infrared bands. It is a widely used vegetation index calculated by using (7). The value of NDVI ranges from +1 to −1. The positive values are representative of healthy green vegetation, and the negative NDVI values indicate non-vegetative cover. In the year 1990, the maximum NDVI or vegetative greenness in Guwahati city was primarily found in north-western and north-eastern parts of the city, ranging from 0.26 to 0.61 (Fig. 8). Whereas, the central part of the city has seen highly concretized and therefore has the least NDVI value of (−0.083 to −0.33). The southern part of the city also records a negative vegetative index due to the presence of agricultural waste land and barren land. Again in 2005, the rapid transformation of land and the increase of built-up area have removed a significant quantity of healthy vegetation cover in the city area. As a result, the city core and most parts of the city recorded negative NDVI values ranging from (−0.05 to −0.23). Whereas, the maximum NDVI value of (0.21 to 0.52) has been recorded especially in the north eastern and south western part of the city due to the presence of hills with dense vegetation areas in the peripheral region of the city (Fig. 8). In the later period, a huge transformation in NDVI has been seen during 1990–2020. For instance, the expansion of built-up areas and construction of road and railway networks have greatly influenced the NDVI of the Guwahati city, particularly in the north-western and south-eastern parts of the city, where the vegetative index witnessed a mark decline during 1990–2020, excepting a few patches (Fig. 8). This is indicative of concretization of few patches of green zones in the dense built-up zones of the city. Owing to the imbalance in the built-up and natural land cover in the central and southern parts of the Guwahati city, it largely records negative NDVI. Further, a small patch of high NDVI is found in Maligaon and Gotanagar area at Nilachal hill, located in the north-western part of the city.

Other prominent green patches of high NDVI ranging from 0.18 to 0.38 correspond to Assam national state Zoo at Zoo hill, Kalapahar and Ramsa hill at north eastern part in the city.

On the other hand, in the year 1990, the maximum NDVI or vegetative greenness in Siliguri was primarily found in north-western, south and south-eastern parts of the city ranging from 0.10 to 0.5 (Fig. 8). Whereas, central part of the city has seen highly concretized and therefore has the least NDVI value of (−0.64). The northern part of the city also records a negative vegetative index ranging from 0.03 to −0.21 due to the presence of agricultural waste land and barren land. Again in 2005, as the city area expanded, significant changes took place; the city core and most parts of the city recorded negative NDVI values ranging from (0.02 to −0.14). Whereas, the maximum NDVI value of (0.13–0.44) has been recorded especially in the north western and south-eastern parts of the city due to the presence of dense vegetation areas in the peripheral region of the city (Fig. 8). In the later period, a huge transformation in NDVI has been seen during 1990–2020. For instance, the expansion of built-up areas and construction of road and railway networks have greatly influenced the NDVI of the Siliguri city, particularly in the north-western and south-eastern parts of the city, where the vegetative index witnessed a mark decline during 1990–2020, excepting a few patches (Fig. 8). This is indicative of concretization of few patches of green zones in the dense built-up zones of the city. Owing to the imbalance in the built-up and

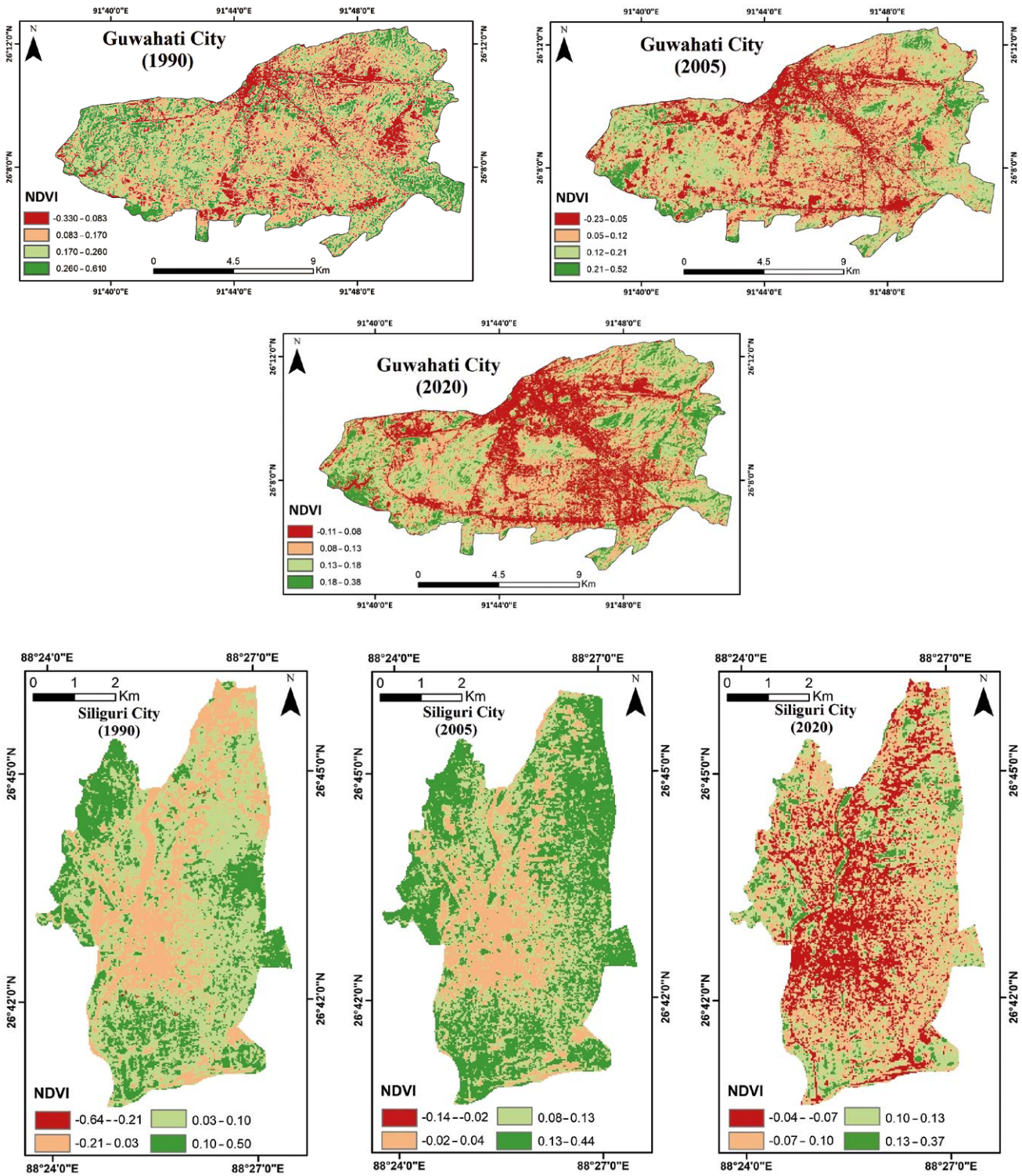


Fig. 8 Changing pattern of urban green space (NDVI) in Guwahati city and Siliguri city for (1990–2020).

natural land cover in the central and southern parts of Siliguri city, it largely records negative NDVI. Further, a small patch of high NDVI of 0.13 to 0.37 is found near Indira Maidan, located in north-western part of the city. Other prominent green patches of NDVI ranging from 0.10 to 0.13 correspond to Surya Sen Park near the Mahananda river and Surya Sen Maidan near SLG park in the city.

4.7 Discussion

The factors responsible for LU/LC changes are many and they vary with respect to different study areas (Turner II and Meyer 1994). In the case of the cities of Guwahati and Siliguri, the factors responsible for changes in LU/LC include deforestation, population growth, migration, multiplicity of urban functions,

encroachment of water bodies, and haphazard infrastructure development. This phenomenon is largely associated with socio-economic and demographic changes in both the cities and their surrounding areas. A comparative analysis of population growth between Guwahati and Siliguri cities from 1990 to 2011 reveals that Guwahati consistently maintained a considerably higher total population compared to Siliguri during the entire period. Despite both the cities exhibiting an almost similar pattern of population growth over the decades, Guwahati experienced considerably higher overall annual growth rate (5.26%) during 1971–2011 as compared to Siliguri (4.24%), but the growth rate became considerably higher in this respect in Siliguri particularly during 1991-2001. Such a high rate of population growth in the cities of Guwahati and Siliguri caused by rapid urban development has brought about significant changes in land use and land cover in both the cities. As population expands agricultural and forest areas are often converted into residential, commercial or industrial zones. This transformation impacts vegetation, as seen in NDVI trend, which typically shows a decline in vegetation cover due to increasing built-up areas, infrastructure expansion and conversion of natural lands into residential and commercial zone. The link between these factors highlights how human activity, driven by population growth, alters ecosystems, leading to reduced greenery and changes in land functions, contributing to environmental degradation and altering natural landscape. Although the transformation of land use and land cover between 1990 and 2020 is quite visible in both the cities, the rate of decline in forest area is higher in Siliguri and rate of increase in built-up area is higher in Guwahati.

According to EBBI index, although the proportion of built-up area in Siliguri city (82%) is considerably higher than that of Guwahati city (57%), both of them require careful planning and urban development strategies including infrastructure development in consideration with their varying circumstances and challenges. Despite Guwahati's higher population growth rate, the higher concentration of built-up area in Siliguri city highlights differing urban expansion patterns and development priorities between the two cities. From an urban planning perspective, the higher built-up area in Siliguri indicates prevalence of more intense urbanization, which could lead to greater challenges in managing infrastructure, services and resources. In contrast, Guwahati city, with a lower proportion of built-up area, although appears to have room for further urban expansion, might face its own challenges related to managing the rapid population growth and required infrastructure development, and protection of the natural landscape. Further, from an environmental sustainability standpoint, Siliguri's more densely built environment could lead to greater environmental pressure, including reduced green space, increased pollution, and greater heat island effects, making the city more vulnerable to climate change impacts. Conversely, Guwahati's relatively lower built-up percentage could offer more opportunities for green spaces, although rapid population growth could put pressure on the city's environmental assets if not managed effectively. Both cities will need to focus on sustainable urbanization practices, such as green building initiatives, waste management and maintaining green spaces, to ensure long-term environmental sustainability.

5. Conclusion and policy suggestion

The foregoing discussion reveals that both the cities of Guwahati and Siliguri have witnessed significant population growth accompanied by unplanned and rapid outward expansion, along with a diversification of urban functions. This phenomenon has significantly altered the original patterns of land use and land cover, with a discernible decline in agricultural land, vegetation cover, and barren land being converted into built-up areas. Consequently, both city areas are confronted with substantial ecological imbalances and heightened human footprints, leading to environmental stress. Over the past three decades (1990–2020), the spatial extent of these cities has expanded by more than four to six times, triggering swift and substantial alterations in land use, particularly at the cost of green cover. The observed progressive decline in NDVI values in both cities suggests possible environmental shifts, including the emergence of urban heat island (UHI) effects and the formation of localized microclimates. As natural land cover is replaced by impervious surfaces like concrete and asphalt, local temperatures intensify. The corresponding reduction in vegetation slows down the natural cooling process through shade and evapotranspiration, exacerbating the UHI effect and reducing the air-purifying functions of urban green spaces, ultimately degrading air quality and public health. To address these challenges, there is a pressing need for the systematic and optimal utilization of land resources in both urban areas to curb unregulated growth. This can be achieved through the stringent implementation of appropriate urban planning strategies and afforestation initiatives, supported by scientific land use zonation, which is a data-driven, evidence-based approach to planning and allocating land uses in a city. Unlike traditional zoning, it relies on legacy administrative decisions, and employs tools such as satellite imagery, environmental assessments, population density studies, and urban growth modelling in GIS platform to determine the most sustainable and appropriate land use patterns. For Guwahati, scientific land use zonation would include identifying and preserving environmentally sensitive zones such as hillocks, flood-prone areas, and wetlands like Deepor Beel. It would involve establishing urban growth boundaries, defining buffer

zones around ecologically and infrastructural critical areas, and conducting suitability analysis based on topography, drainage, accessibility, and infrastructure availability. Although Guwahati falls under the Smart City Mission and is guided by the Master Plan 2025, the progress of implementation has been sluggish and inconsistent, limiting the potential impact of these initiatives. There is an urgent need to expedite and effectively enforce these frameworks in line with updated geospatial and demographic data. In contrast, Siliguri is not included under the Smart City Mission, although a City Development Plan (CDP) has been launched. The government has taken several initiatives toward systematic land use planning, but the absence of a formally implemented Master Plan or integration with a Smart City framework hampers long-term sustainability. Thus, there is a critical need for the preparation and implementation of a comprehensive Master Plan, ideally supported by smart city principles, to guide urban development and ecological conservation in Siliguri. Ultimately, integrating scientific land use zonation with existing urban planning frameworks will be key to ensuring environmentally sound, resilient, and liveable cities in both Guwahati and Siliguri.

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Assessment of factors influencing access to residential land in urban border communities of Imeko/Afon Local Government Area of Ogun State, Nigeria: A gender dimension

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ABSTRACT
This article examines the factors influencing access to residential land among men and women in Ogun State border communities, Nigeria. A multi-stage sampling technique was employed to select 411 male and female homeowners. Copies of the questionnaire were administered to 362 respondents (196 males and 166 females), representing 54% male and 46% female homeowners. Frequency distribution, percentages, factor analysis, binary probit regression, and correlation analysis were utilized to analyze the data collected from male and female homeowners. The study reveals that the proportion of female respondents with insecure access is higher than that of their male counterparts. This indicates that women are more land-insecure compared to men. The study shows that affordability, land availability, procedural issues, security of tenure, and personal factors were found to influence men's access to residential land, while affordability, land availability, security of tenure, personal, and procedural issues were the factors among women. The use of binary probit regression analysis indicates that lower levels of affordability, limited land availability, and weaker socioeconomic status tend to reduce men's likelihood of access to residential land, while improvements in tenure security and procedural conditions often increase their probability of land access. In contrast, limited land availability and bureaucratic barriers tend to reduce women's likelihood of access, while an increase in financial capacity, tenure security, and stronger socioeconomic status enhances their access to residential land. Findings from the correlation analysis demonstrate that access-related land factors of male homeowners are positively influenced by socio-economic variables, while female homeowners experience predominantly negative associations, particularly with marital status, household size, and income. The study concluded that access to residential land is influenced by different factors, and these factors significantly influence the level of access among men and women.

KEYWORDS
residential land; access to land; housing; gender; border communities; Nigeria

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1. Introduction

The issue of land is a controversial topic among scholars in the Global South (Adebayo 2018; Chrinus et al. 2024; Oladehinde et al. 2024; Toulmin 2009). Access to land is central to residential development, a major element in urban development. Adequate land supply is generally recognized as a prerequisite for sustainable housing delivery systems. However, limited supply or availability of residential land in cities and emerging urban areas has made access to land for housing development a major issue. In sub-Saharan African countries, urban land is becoming a commodity to acquire, and its acquisition often goes to the highest bidder (Lawal and Adekunle 2018).

Land in recent times constitutes a greater percentage of housing construction costs in urban areas of Nigeria, and only privileged individuals with political and economic power have access to it through government allocation or the formal land market (Kuma 2016). The urban poor, who are average income earners, often struggle to gain access to land for housing development. Land access for housing development is a major challenge among the urban poor in Nigeria, especially in urban border communities. These communities have recently become urbanized due to uncontrolled migration from neighboring countries in western Nigeria and other areas within the country (Oladehinde et al. 2023; Ojo et al. 2019). The population increase has led to high pressure on residential land, making access increasingly competitive. As a result, available residential land is often unaffordable, affordable land is inaccessible, and accessible land is insecure. According to Bernstein (2005), access to land is frequently hampered by issues such as incessant conflict and litigation, fraudulent land sales, marginalization of non-landholding families, high land costs, stringent titling procedures, communal conflict, and tenure insecurity. Other issues include bureaucratic and administrative bottlenecks, as well as lengthy and challenging processes for obtaining permissions and approvals (Oladehinde et al. 2023; Udechukwu 2008; Gbedegesin et al. 2016). While previous studies have shown that land accessibility is a significant urban development problem regarding housing delivery in Nigeria, there remains a dearth of gender-focused studies, particularly with evidence from international border communities in Ogun State, Nigeria.

Urban communities in Nigeria's border region are struggling to cope with the increasing demand for land for housing development. This demand is expected to escalate in the near future due to anticipated population growth. Accessibility to residential land in these communities is a major issue, particularly given the limited supply of land. Urban poor from other regions may find it challenging to build their own homes due to the bureaucratic process involved in land access, potentially threatening their access to decent and sustainable housing. Ensuring secure access to residential land in Nigeria's border communities, especially among low-income groups where the informal market prevails, has become a critical issue. The processes, methods, and procedures for land access, as well as the factors influencing it, may have significant implications for housing development among men and women in these communities. Access to land is deeply influenced by gender, with women facing significant disadvantages compared to men due to discriminatory customary practices, legal, and financial constraints. Women's access is typically mediated through their relationships with male relatives, making it insecure and easily revoked (Oladehinde 2016). These challenges often limit their ability to secure land independently, reinforcing gender inequality in housing and land ownership (Cotula and Mathieu 2008; Opoku 1997)

Apart from this, the government has made efforts to ensure easy access to urban land for residential development through the formulation of land and housing policies. For instance, the Land Use Act of 1978 was formulated to address the problem of land accessibility. The Act vested urban land in the Governor of the state, to be held in trust and administered for the use and common benefit of all Nigerians, irrespective of gender. Nonetheless, access to land remains one of the most significant obstacles to urban housing delivery (Ogu and Ogbuozobe 2001; Oladehinde et al. 2018). The National Housing Policy (NHP 2006) was also formulated to ensure that all Nigerians have access to safe and healthy accommodation at an affordable cost. The policy aimed to make building plots available at the right time, in the right place, and at a reasonable price for those willing to build. Although the policy is well-intentioned, not much progress has been made in solving the problem of land access in Nigeria's border regions. While the policies emphasize equal access to land, regardless of gender, in practice, land accessibility for residential development often varies between men and women (Morenikeji et al. 2022). This variation may be attributed to different factors.

Gender differences in access to and control of land resources remain a significant concern in Sub-Saharan Africa, particularly in Nigeria. To address this, the Sustainable Development Goals (SDGs) 1 and 5, which aim to reduce poverty and promote gender equality in rights and control over land resources by 2030, are crucial. Achieving this goal requires understanding the socio-economic attributes of men and women, methods of land access, and factors influencing their access to residential land in emerging urban communities, especially in border areas. This study will contribute to the body of knowledge on land access dynamics for men and women in urban border communities. This study aims to examine the factors influencing access to residential land among men and women in Ogun State's emerging urban

areas, using border communities in Imeko-Afon Local Government Area (LGA) as a case study. The aim is addressed based on quantitative analysis of data from own survey, which compares subsamples of male and female homeowners. To achieve this aim, the study addresses the following questions: 1. What are the socioeconomic characteristics of men and women in the study area? 2. How do men and women access land? 3. What factors influence men's and women's access to land for housing development in these border communities?

2. Literature review: Conceptual issues

Land is a critical asset for economic, social, and cultural life, shaping power relations and individual identities (IFAD 2006). Access to land goes beyond physical occupation—it also entails rights that are socially or legally recognized, enabling secure usage and control of land (UN-HABITAT 2008; Cotula et al. 2006). According to Oladehinde et al. (2023), residential land access includes the legal and physical ability to obtain land for housing, which can be secure or insecure. Secure access involves acquiring legal titles or occupancy rights, ensuring ownership or use, while insecure access occurs when individuals lack proof of ownership or occupancy rights. Secure access to residential land is crucial for shelter, livelihood security, poverty alleviation, and sustainable development (UN-HABITAT 1996).

Scholars have conceptualized land access using several criteria such as availability, affordability, ease of transaction, and tenure security (Omirin 2003). Availability refers to the presence of usable land within a locality, while affordability reflects an individual's capacity to obtain land within their financial means. The high costs of formal land transactions in countries like Nigeria have been noted as major barriers (World Bank 2009; Marx 2007). Tenure security implies protection from forced evictions and fair compensation during land acquisition (Oyedeji 2018). While several studies (Omirin and Odudu 2012; Oladehinde et al. 2018, 2023; Owoeye and Adedeji 2015) have used these parameters, some studies have also added personal attributes of the land user as part of the contributing factors to land inaccessibility (Oladehinde et al. 2023; Mearns 1999; Kuusaana et al. 2013). Research has shown that land inaccessibility disproportionately affects vulnerable groups, including the poor and women. This study adopts these parameters to evaluate the factors affecting land access for residential development among men and women in the border region of Nigeria.

Access to land is typically achieved through government allocation, inheritance, purchase, gifts, and rental or lease (Nwuba 2017; Arjjumend and Seid 2018). However, the formal land administration system often excludes low-income groups due to bureaucratic inefficiencies and corruption (Durand-Lasserve 2005; Mabogunje 2003). In response, many urban residents rely on informal markets, which have become the dominant mechanism for residential land access (Durand-Lasserve 2006; Kuma 2016). Despite their accessibility, informal markets are plagued by insecure land titles, high transaction costs, and legal disputes (Rakodi and Leduka 2004; Kironde 2006). These systemic challenges underscore the inadequacy of current land governance structures and administration frameworks (UN-HABITAT 2008). Olujimi and Iyanda (2013) further corroborate that the land rights of the urban poor are inadequately safeguarded, irrespective of their socio-economic status. Consequently, the absence of effective governance and land administration mechanisms has rendered informal land transfers and ownership vulnerable, posing significant implications for poor men and women seeking to secure land for residential development.

Land access in sub-Saharan Africa is often determined by gender. Traditional and customary land tenure systems, which govern the majority of land in the region, tend to favour male ownership and inheritance, thereby marginalizing women in land acquisition processes. Under customary law, land is typically passed down through male lineage, leaving women dependent on male relatives – such as fathers, husbands, or brothers – for access (Cotula and Mathieu 2008; Toulmin 2009). As a result, women's land rights are usually secondary, insecure, and conditional. This patriarchal structure is reinforced by socio-cultural norms that validate male control over land and property, excluding women from critical land transactions such as grants, transfers, or inheritance (Oladehinde 2016). Even where legal reforms exist to promote gender equality in land rights, implementation remains weak due to persistent customary practices and limited awareness among women of their legal entitlements.

Beyond cultural and institutional barriers, women also face economic and procedural constraints that hinder their ability to access land for housing. Women in Nigeria often have lower levels of education and limited access to high-income employment, reducing their financial capacity to purchase land or qualify for credit (Olawore 2008; Olugbemi 2015). Additionally, land acquisition through formal channels is often costly, bureaucratic, and time-consuming, requiring documentation and collateral – such as existing land titles – that women are less likely to possess (Opoko 1997). This makes it difficult for many women to secure loans or navigate complex land registration systems. Consequently, women are pushed toward informal and less secure means of acquiring land, which expose them to risks such as eviction, disputes, or lack of tenure security. These gender-specific challenges not only restrict women's access to safe and adequate housing but also limit their ability to invest in long-term development and economic stability.

2.1 Review of empirical studies

Several studies have examined gender dimensions of land accessibility in Nigeria, but few focus on border communities. For instance, Ajayi and Adebayo (2017) found that land access in Akure was primarily through purchase, inheritance, government allocation, and gifts, with occupation, income, and education being key determinants. Morenikeji et al. (2022) highlighted that only 16% of women in Minna had land access compared to men, attributing this to cultural practices, religious bias, illiteracy, and limited female representation. Similarly, Owoicho et al. (2023) found that men had more access to land due to high costs, customs, communal tenure, and credit access. Popoola et al. (2023) and Masuku et al. (2023) also identified cultural, religious, and legal barriers to women's land access. Despite these studies, little research has addressed gendered land access in Nigeria's border communities.

In addition to gender-focused studies, broader research on land accessibility (Famudehin 2015; Ibrahim et al. 2024; Nagya and Udoekanem 2022; etc.) has largely ignored the unique dynamics of border regions. Famudehin (2015) noted economic and bureaucratic constraints, such as land cost and corruption. Ibrahim et al. (2024) identified socio-demographic and educational factors as key influences. Other studies emphasized land titling, security of tenure, affordability, and acquisition procedures. For example, Gbadegesin et al. (2016) highlighted tenure security, while Omirin (2003) stressed affordability and transaction ease. Nuhu (2019) critiqued Tanzania's formal land system for its complexity, and Adebayo (2018) identified occupation as the most important factor in Kogi State.

Few studies have examined land accessibility in border areas, and those that exist (Oladehinde et al. 2018; Oladehinde et al. 2017) focus mainly on migrants, neglecting gender differences and residents' populations. While Oladehinde et al. (2023) addressed land access for housing development, identifying affordability, tenure security, procedural factors, personal attributes, and land availability as important determinants. Despite these, the study did not explore the gendered dimensions of land access for residential development. In light of these gaps, the need for research on gender-specific factors influencing land access in emerging urban communities along international borders of sub-Saharan Africa, particularly Nigeria is evident. Existing studies have not sufficiently categorized these factors or addressed their gender implications. This study, therefore, aims to fill that gap by examining gendered factors influencing residential land access, with the goal of informing policy solutions that enhance residential land access and promote equitable and sustainable urban development.

2.2 Conceptual framework

The conceptual framework for this study was inductively developed based on the existing literature on gendered land access, drawing on recurring variables and dimensions identified across multiple studies. It outlines the pathways through which gendered access to land for residential development can be assessed, incorporating key parameters such as land accessibility, the nature of land access, and socio-economic attributes. Specifically, land accessibility is characterized by several variables, which are grouped into four main categories: land affordability, land availability, security of tenure, and procedural factors – categories synthesized from various studies in the literature. Land accessibility for housing among men and women can be conceptualized into three dimensions (Fig. 1). Prior research has demonstrated that these dimensions are effective for measuring land accessibility in the context of housing development (Olujimi and Iyanda 2013; Nwuba 2017; Owoeye and Adedeji 2015; Oyedeji 2018; Adebayo 2018; Oladehinde et al. 2023). Guided by this framework, the present study examines the socio-economic characteristics of men and women, the modes through which they access

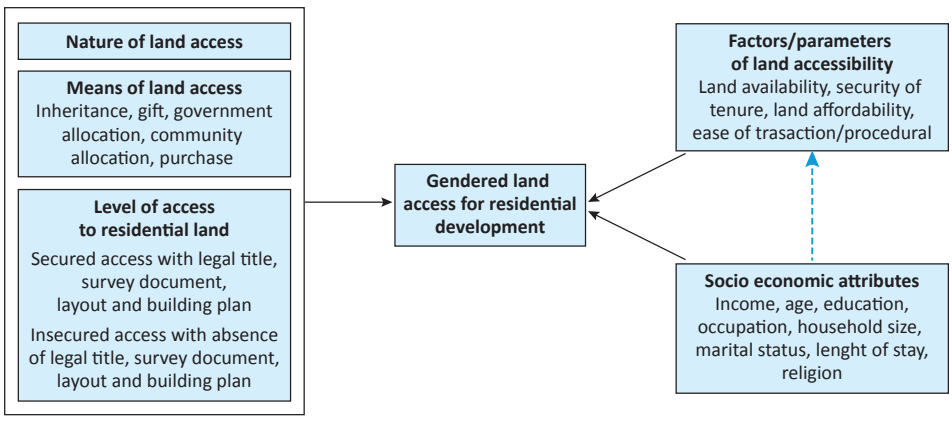

Fig. 1 Conceptual framework on gendered land access for residential development in urban border communities.
Source: Author's compilation (2025).

land, and the factors influencing land access for residential development in the study area. The specific indicators and variables used for measurement are presented in Fig. 1.

3. Methods and materials

3.1 Study area

The study was conducted in the border communities of Ogun State, Nigeria. These communities encompass a range of settlements, from small hamlets to larger villages and towns. This study focuses on emerging urban communities located between 1–50 kilometers from the international boundary as established by Harvey (2008). As a result of urbanization and population increase, residential land use, as observed by Oladehinde et al. (2023), has become the common land use pattern of major towns and emerging suburban areas in the border region. Additionally, the expansion of governmental activities and the rise of commercial hubs in the region have transformed land into both a status symbol and a valuable investment asset for the local population. Importantly, the porosity of Nigeria's border has significantly impacted these communities, as urbanization and population increase are further driven by uncontrolled migration from Nigeria's hinterland and neighboring countries such as the Benin Republic, Ghana, Togo, and Burkina Faso (Oladehinde et al. 2023). The study area, Ogun State, Nigeria, has three (3) border Local Government Areas (LGAs) that share a boundary with the Benin Republic (Fig. 2). These include Ipokia, Yewa North, and Imeko/Afon.

3.2 Sampling procedure and data collection

A multistage sampling procedure was employed to select respondents in the study area. In the first stage, random sampling was used to select one Local Government Area (LGA) from the three identified border LGAs in Ogun State. The selected LGA was Imeko/Afon. In the second stage, four urban communities

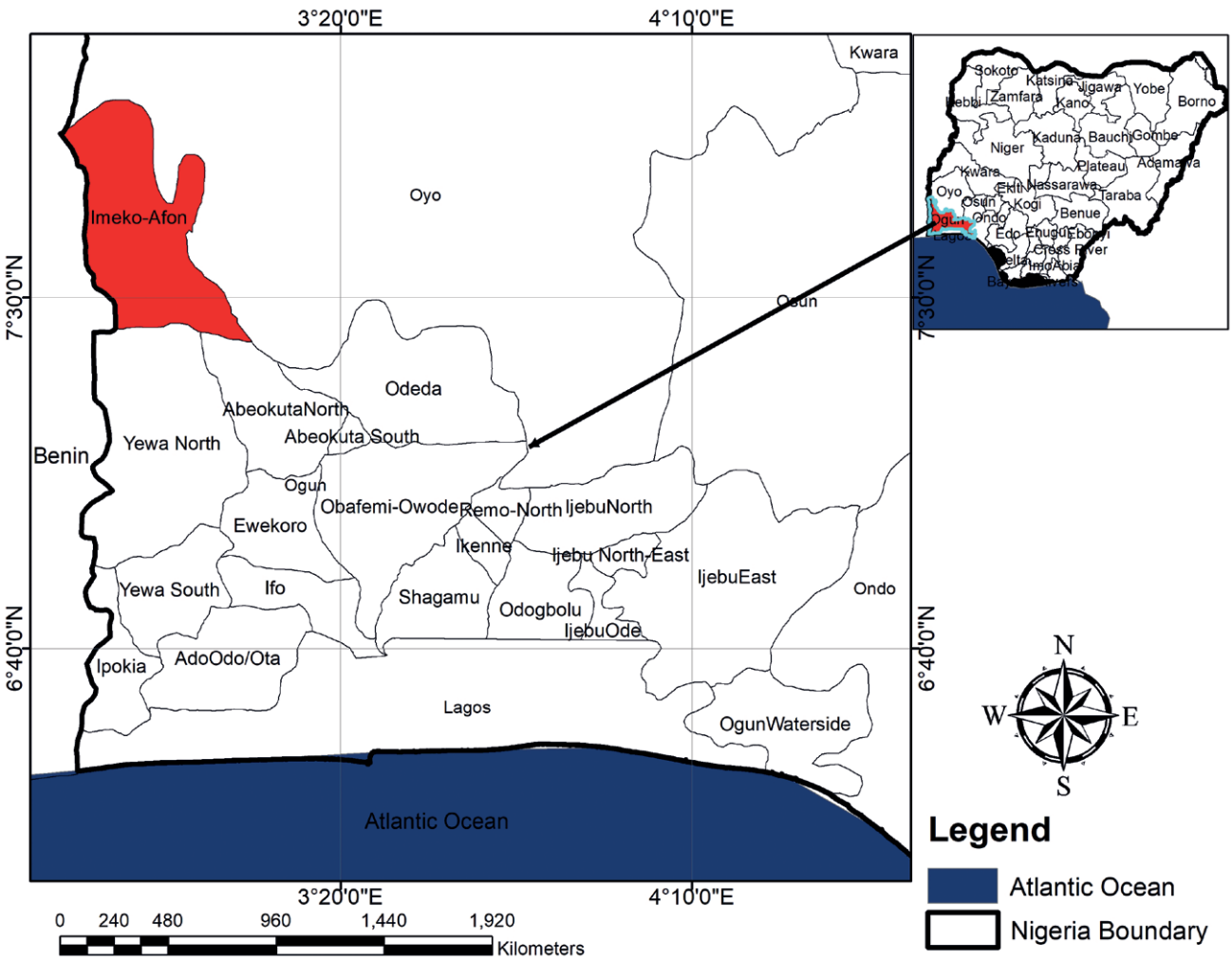

Fig. 2 Nigeria, indicating Ogun State and Imeko Afon Local Government Area.
Source: Cooperative information network (COPINE 2024).

within Imeko/Afon LGA were selected: Iwoye, Ilara, Idiayin, and Idiemi. The communities were purposively selected based on criteria such as the presence of urban development, high population density, ongoing urbanization, and notable government and economic activities within a 50 km radius of the international border (Ojo et al. 2019; Oladehinde et al. 2023; Harvey 2008). The third stage involved identifying and selecting residential buildings within the study area. Specifically, the study focused on residential houses constructed through self-help efforts by the owners, as identified during the pilot survey. The majority of sampled buildings were owner-occupied. This selection is consistent with findings from previous studies (Gbadegesin et al. 2016; Oladehinde et al. 2023).

The total number of habitable residential buildings in the study area was determined using a combination of Google Earth software and a physical building count conducted during the pilot survey. A total of 8,985 residential buildings were enumerated across the four selected communities, comprising 1,959 in Iwoye, 2,647 in Ilara, 1,725 in Idiayin, and 1,856 in Idiemi. Homeowners were selected through systematic random sampling. In each community, the first owner-occupied residential building was randomly selected, after which every 20th owner-occupied building was included in the sample. In cases where a homeowner was not residing in the building, the next eligible owner-occupied building was selected. At the end of this process, a sample size of 411 residential buildings – representing 5% of the total – was selected and surveyed (Tab. 1). This sample size was considered valid, adequate, and reliable, as it aligns with established guidelines recommending sample sizes between 100 and 1,000 for regional and district-level studies (Casley and Lury 1991). Of the 411 questionnaires administered to respondents, 362 were completed and retrieved, representing a response rate of 88.01%. The sampled respondents were split into two sub-samples of male and female homeowners of the selected buildings, as they were deemed capable of providing reliable information regarding issues related to residential land accessibility in the study area. The selected male and female homeowners during the time of the survey refer to the individuals who are recognized as the owners of a house or property, be it male or female. The questionnaire was self-administered among the selected homeowners and was divided into three sections. The first section addressed the socio-economic characteristics of the respondents; the second focused on the methods and levels of land access among men and women in the study area; and the third examined the parameters of residential land access within the study area.

Tab. 1 Residential buildings and sample size of the study area.

S/N	Urban communities	Number of buildings	Sample size (5%)	Number of the retrieved questionnaire
1	Iwoye	1959	98	88
2	Ilara	2647	133	119
3	Idiayin	1725	87	80
4	Idiemi	1856	93	75
7	Total	8990	411	362

The study sampled 362 respondents, consisting of 54% male and 46% female homeowners. The 46% female representation is considered valid and aligns with findings from prior studies in Sub-Saharan Africa, which reported similar or higher proportions of female home or land owners, such as Ajayi and Adebayo (2017) in Nigeria (39.37%), Quansah (2012) in South Africa (35%), and Kuusaana et al. (2013) in Ghana (58%). This representation is particularly appropriate given the urban context of the study, where female land ownership and independence are increasingly prevalent in urban communities of Sub-Saharan Africa.

3.3 Data analysis

The data collected for this study were analysed using both descriptive and inferential statistical methods. Descriptive statistics, including tables, frequency distributions, and percentages, were employed to examine the socio-economic attributes of respondents, levels of access to residential land, and the method of land access. Inferential statistical techniques, including factor analysis, probit regression, and correlation analysis, were employed in the study. Twenty-three variables identified from the literature served as parameters for measuring the factors affecting land accessibility for housing development. Respondents were asked to provide their perceptions or experiences on these variables using a five-point Likert scale, ranging from 5 (strongly agree) to 1 (strongly disagree).

Factor analysis was subsequently used to reduce the number of variables by grouping them into a smaller set of components, using varimax rotation. Variables with factor loadings below 0.50 were excluded from the final component structure (Oladehinde et al. 2023). The retained variables were extracted, grouped, and renamed to reflect the underlying dimensions. As observed by Aiken et al. (2008), factor analysis is particularly useful for eliminating multicollinearity and uncovering latent variables.

A binary probit regression model was used to estimate the likelihood of secure residential land access, with the dependent variable coded as 1 for secure access and 0 otherwise. The independent variables were the extracted factor scores that were derived from factor analysis. The probit model assumes a latent (unobserved) continuous variable underlying the binary outcome, with normally distributed error terms. Coefficients indicate the direction and

significance of each factor's influence on the likelihood of secure access.

The Pearson product-moment correlation coefficient is a measure of the strength and direction of association that exists between two variables measured on at least an interval scale. Pearson Correlation was used to examine the relationship between extracted factor scores (affordability, land availability, tenure security, and ease of transaction) and the socio-economic characteristics of male and female homeowners (age, income, educational qualification, occupation, and length of stay) in the study area. To achieve this, extracted factors associated with access to residential land were correlated individually with the socioeconomic attributes of men and women.

3.4 Definition of central variables

The study utilized 23 variables sourced from existing literature, which were grouped into five key parameters – land availability, affordability, ease of transaction, tenure security, and personal attributes – through factor analysis. Land availability refers to the physical land space available for various uses within an area, considering its origin and any encumbrances that may limit its use, while Land affordability is the ability of individuals and households to access and afford land for housing and other purposes, given their income and land costs. Ease of transaction refers to the process of navigating the land market and formalizing transactions to obtain valid and secure land titles, while security of tenure involves protection against interference or trespass and adequate compensation in case of compulsory acquisition. Personal attributes include the socioeconomic characteristics (such as age, income, marital status, occupation, length of stay, among others) of the land users/ homeowners (male and female respondents). The factor scores of the extracted five parameters were used in a binary regression model as independent variables, while the nature of land access was used as the dependent variable. A binary variable, such as secure = 1 or insecure = 0, was used in this study. In this study, secure access to residential land involves land acquisition that is backed up with legal titles or right of occupancy to ensure ownership or the right to use the land for housing, while insecure access to residential land means land ownership that lacks legal titles or right of occupancy.

4. Results

4.1 Socioeconomic characteristics of male and female homeowners

Socio-economic characteristics of male and female homeowners include the variables influencing residential land access in the study area. These variables were incorporated into the factor analysis, binary probit regression, and correlation analysis. Variables of socioeconomic characteristics of men and women in the study area are presented in Tab. 2.

Tab. 2 shows that the majority of respondents in both categories were within the 31–60 age range. Most respondents were married and had relatively small household sizes. Income data reveal that over half (52.0%) of the male respondents earned between ₦18,001 and ₦55,000 per month, whereas most female respondents earned below ₦18,000, indicating a gender disparity in income levels in favour of men. Gender disparity in the level of income might have a significant impact on women's access to and control over land for residential development, particularly in patriarchal societies where customary norms favour men in land ownership. This disparity might lead to women having insecure access to residential land. It can also determine the type of investment in the land. In terms of educational attainment, 41.8% of male respondents had completed secondary education, while the highest proportion of female respondents (53.6%) had attained primary education. This suggests that male and female respondents possessed at least basic literacy skills. Regarding occupational status, the majority of male respondents (73.5%) were self-employed, whereas most female respondents (51.8%) were employed in civil service. Additionally, more than one-third of both male (33.2%) and female (32.5%) respondents had resided in the study area for between 11 and 15 years. The close disparity of length of stay between male and female respondents might strongly impact land access, particularly for women, where land access is tied to long-term occupancy or inheritance.

Tab. 3 presents data on the level of access to residential land among male and female respondents in the study area. The findings reveal that 71.4% of male respondents reported insecure access to land for housing development, while 28.6% had secure access. Among female respondents, 81.9% indicated insecure access, compared to 18.1% who had secure access. This indicates that a higher proportion of men have secure access to land relative to women, whereas a greater proportion of women experience insecure access compared to their male counterparts. These findings suggest that most residential land access, particularly among women, is not supported by legal documentation. This disparity may have significant implications for equitable land access and residential development in the study area.

4.2 Methods of access to residential land

Respondents were also asked to indicate their method of access to residential land (Tab. 4). Among male respondents, the most common method was land purchase (35.3%), followed by community allocation (26.0%), government allocation (18.7%), inheritance

Tab. 2 Socioeconomic characteristics of men and women in the study area.

		Male (N = 196)		Female (N = 166)	
		Frequency	Percentages	Frequency	Percentages
Age	below 30 years	20	10.2	69	41.6
	31–60 years	163	83.2	97	58.4
	above 60 years	13	6.6	0	0.0
Religion	Christianity	79	40.3	78	47.0
	Islam	14	7.1	22	13.3
	traditional	89	45.4	31	18.7
	others	14	7.1	35	21.1
Marital status	single	20	10.2	21	12.7
	married	132	67.3	129	77.7
	separated	33	16.8	0	0.0
	widow/widower	11	5.6	16	9.6
Household size	small	122	62.2	116	69.9
	medium	70	35.7	44	26.5
	large	4	2.0	6	3.6
Monthly income	below 18,000	34	17.4	84	50.6
	18,001–55,000	102	52.0	66	39.8
	above 55,001	60	30.6	16	9.6
Educational status	no formal education	26	13.3	63	38.0
	primary school	75	38.3	89	53.6
	secondary school	82	41.8	14	8.4
	polytechnic/college of education	13	6.6	0	0.0
Occupation	unemployed	2	1.0	6	3.6
	farming	43	21.9	53	31.9
	civil servant	7	3.6	86	51.8
	self employed	144	73.5	21	12.7
Length of stay	1–5 years	51	26.0	55	33.1
	6– 0 years	44	22.4	23	13.9
	11–15 years	65	33.2	54	32.5
	above 16 years	36	17.3	34	20.5

Tab. 3 Level of access to residential land.

Level of access to residential land	Men (N = 196)		Female (N = 166)	
	Frequency	Percentages	Frequency	Percentages
secure access	56	28.6	30	18.1
insecure access	140	71.4	136	81.9

(13.7%), and gift (6.2%). Similarly, among female respondents, the predominant method of land access was also purchase (31.0%), followed by government allocation (26.0%), community allocation (23.6%), inheritance (13.5%), and gift (5.8%). These findings suggest that, for both male and female respondents, land purchase constitutes the most prevalent means of accessing residential land in the study area. Although most male and female respondents have access to land through purchase, women may sometimes face significant barriers to accessing land, even when it is acquired through purchase. This could stem from deeply ingrained gender norms and discriminatory customary laws in patriarchal societies that are emerging urban communities.

4.3 Factors associated with access to residential land

The varimax-rotated component matrix of factor analysis, reveals five extracted factors with eigenvalues greater than 1. Out of the 23 variables initially

Tab. 4 Gender distribution of the method of access to residential land.

Method land access	Male			Female		
	Responses		Percent of cases	Responses		Percent of cases
	N	Percent		N	Percent	
Inheritance	66	13.7%	33.8%	51	13.5%	32.7%
Gift	30	6.2%	15.4%	22	5.8%	14.1%
Government allocation	90	18.7%	46.2%	98	26.0%	62.8%
Community allocation	125	26.0%	64.1%	89	23.6%	57.1%
Purchase	170	35.3%	87.2%	117	31.0%	75.0%
Total	481	100.0%	246.7%	377	100.0%	241.7%

Note: Higher than the total survey because of multiple responses.

included, five components met the eigenvalue criterion. Additionally, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.627 for men and 0.683 for women, and Bartlett's test of sphericity was significant at $p < 0.000$. These results confirm that the data were suitable for principal component (factor) analysis. Factors with an eigenvalue greater than one were retained and named.

Results of the extracted factors in Tab. 5 reveal the significant component loadings of 0.50 and above that explain the underlying factors associated with access to residential land in the study area. The eigenvalues indicate the strength or importance of each factor, while the percentages of variance represent the amount of overall variation in responses explained by each factor. The factor with the highest eigenvalue

Tab. 5 Sorting and grouping of the extracted factors using the loading items and values for men and women.

Male					Women				
Renamed factors and list of variables	Loading vari-ables	Eigen-value	% variance explained	Cumul. % variance explained	Renamed factors and list of variables	Loading vari-ables	Eigen-value	% variance explained	Cumul. % variance explained
Factor 1 – Affordability		5.896	25.635	25.635	Factor 1 – Affordability		5.222	22.706	22.706
Price of residential land in relation to income of household	.963				Price of residential land in relation to income of household	.931			
Price of purchasing land	.957				Price of purchasing land	.931			
Financial condition	.955				Financial condition	.913			
Price of serviced residential land with convenient access to the road	.913				Price of serviced residential land with convenient access to the road	.833			
Factor 2 – Land availability		3.61	15.694	41.329	Factor 2 – Land availability		4.109	17.865	66.041
Residential land is not readily available	.827				Access road to available residential plots is in poor condition	.981			
Pressure on land used for residential purposes	.823				Purpose of acquiring the land	.981			
Size of residential land available (Plot size)	.694				Land conflict	.816			
Purpose of acquiring the land	.692				Pressure on land used for residential purposes	.690			
Access road to available residential plots is in poor condition	.642				Size of residential land available (Plot size)	.584			
Land conflict	.583								

Factor 3 – Procedural		2.875	12.501	77.357	Factor 3 – Security of tenure		3.263	14.185	36.891
Transparency in the process of acquiring land	.807				Type of land holding (private, communal, state, open)	.941			
Property right (Bundle of right)	.746				Land security without title documents	.913			
Bureaucratic bottleneck/protocols	.658				Traditional belief (Culture practices)	.794			
Cost of transaction	.640				Type of land tenure practices in this area	.723			
Difficulties with the land registration procedure	.727								
Factor 4 – Security of tenure		2.77	12.043	53.372	Factor 4 – Personal		2.802	12.186	78.227
Type of land holding (private, communal, state, open)	.935				Household size	.911			
Type of land tenure practices in this area	.924				Occupation	.696			
Land security without title documents	.864				Length of stay	.681			
Traditional belief (Culture practices)	.693				Income	.525			
Factor 5 – Personal attributes		2.641	**11.484**	**64.856**	Factor 5 – Procedural		2.596	11.285	48.176
Occupation	.859				Transparency in the process of acquiring land	.800			
Income	.784				Difficulties with the Land Registration Procedure	.799			
Length of stay	.601				Bureaucratic bottleneck/protocols	.679			
					Cost of transaction	.611			
Extraction method: Principal component analysis. Rotation method: Varimax with Kaiser normalization. a. Rotation converged in 9 iterations.					Extraction method: Principal component analysis. Rotation method: Varimax with Kaiser normalization. a. Rotation converged in 11 iterations.				

Tab. 6 Probit regression analysis of the associated factors and level of access to residential land for men and women.

Men					Women				
Associated factors	**Coef.**	**Std. Err.**	**Z**	**P>z**	**Associated factors**	**Coef.**	**Std. Err.**	**Z**	**P>z**
Affordability	−.3757162	.1120875	−3.35	0.001***	Affordability	.0482529	.1740624	0.28	0.082*
Land availability	−.3945553	.1174035	−3.36	0.001***	Security of tenure	.4041526	.1801170	2.24	0.025**
Security of tenure	.2159212	.0981845	2.20	0.028**	Procedural	−.887673	.2073862	−4.28	0.000***
Personal attribute	−.1309648	.1007507	−1.30	0.094*	Land Availability	−.5542318	.1505420	−3.68	0.000***
Procedural	.1390949	.0726016	1.92	0.050**	Personal attribute	.2265544	.1492997	1.52	0.029**
_cons	−.6822504	.1082790	−6.30	0.000	_cons	1.549946	.2391911	6.48	0.000
Number of observations = 196; Pseudo R2 = 0.5417; LR Chi-Square (5) = 33.24; Prob > Chi2=0.0000; Log Likelihood = −00.63998; *** Significant at 1% level, ** significant at 5% level					Number of observations = 166; Pseudo R2 = 0.6823; LR Chi-Square (5) = 59.97; Prob > Chi2=0.0000; Log Likelihood = −48.448041; *** Significant at 1% level, ** significant at 5% level, * significant at 10% level				

within the male category was affordability (5.861), next to this was land availability (3.610), procedural (2.875), security of tenure (2.77), and personal attributes (2.641). The percentages of the variance further show that the key factors influencing men's access to residential land included: Affordability (25.64%), Land Availability (15.69%), Procedural (12.50%), Security of Tenure (12.04%), and Personal (11.48%)

factors. On the other hand, affordability has the highest eigenvalue among the female homeowners, next to this was land availability (4.109), security of tenure (3.263), personal attributes (2.802) and procedural (2.596). The percentages of the variance reveal that the key factors were: Affordability (22.71%), Land Availability (17.87%), Security of Tenure (14.19%), Personal (12.19%), and Procedural (11.29%). The combined factors explained 77.36% and 78.23% of the total variance for male and female respondents, respectively, reflecting a robust model appropriate for explaining factors associated with access to residential land among men and women in the study area. The findings suggest that financial considerations, land availability, procedural issues, and tenure security are central factors influencing land access for housing development among men. For women, financial considerations, land availability, tenure security, and personal characteristics emerged as the most influential, according to their respective levels of importance. It could be inferred that land access for housing development among male and female homeowners is affected by shared and distinct factors. While affordability and land availability are universal barriers, procedural, tenure, and personal factors affect male and female respondents differently.

Following the classification of factors influencing access to residential land, the extracted and renamed components were employed as independent variables in a binary probit regression analysis (Tab. 6). This regression model was used to determine the significance of these extracted factor scores in predicting respondents' level of land access (categorized as secure or insecure access). For male respondents, the diagnostic statistics presented in Tab. 6 indicate that the chi-square (LR) value is significant at the 1% level, confirming that the explanatory variables collectively influence access to residential land. The model's Pseudo R-squared value shows that 54.1% of the variation in access to residential land is explained by the independent variables. The signs of the coefficients indicate the direction of the relationship: a positive sign denotes an increase in the probability of the extracted factors in the level of access to residential land, while a negative sign implies a decrease.

The regression results show that the coefficients for affordability, land availability, and personal factors are negative and statistically significant, while those for security of tenure and procedural factors are positive and significant at the 1%, 5%, and 10% levels. Specifically, affordability (−0.3757), land availability (−0.3946), and personal factors (−0.1310) negatively influence access to residential land, indicating that lower affordability, limited land availability, and weaker socioeconomic status reduce men's likelihood of secure access. Conversely, the coefficients for tenure security (0.2159) and procedural factors (0.1391) are positively signed, implying that improvements in tenure security and procedural clarity increase the probability of secure land access. This indicates that unaffordability and unavailability of land with lower socioeconomic status of the respondents, tend to reduce the level of access to residential land, while higher levels of tenure security and procedures of land transaction often increase the level of access to residential land among the male respondents. These findings align with the results reported by Oladehinde et al. (2023) and Omirin (2003).

In the case of female respondents, the diagnostic statistics also reveal a significant chi-square (LR) value at the 1% level, indicating that the explanatory variables jointly influence access to residential land. The model's Pseudo R-squared value of 59.9% reflects a good explanatory fit. The results show that land availability and procedural factors have negative and significant coefficients, while affordability, security of tenure, and personal factors are positively significant at the 1%, 5%, and 10% levels. Specifically, the coefficients for procedural (−0.8877) and land availability (−0.5542) factors suggest that limited land availability and bureaucratic barriers reduce the likelihood of secure land access for women. On the other hand, the coefficients for affordability (0.0483), security of tenure (0.4042), and personal factors (0.2266) indicate that increased financial capacity, secure tenure, and stronger socioeconomic status enhance women's access to residential land.

In summary, the study establishes that access to residential land is significantly influenced by a range of factors that differ in importance for men and women in urban border communities. For men, affordability, land availability, and personal characteristics act as barriers, while tenure security and procedural facilitate access. In contrast, women are more likely to gain secure access through affordability, tenure security, and personal capacity, but face constraints due to land availability and procedural complexity.

4.4 Correlation between socio-economic characteristics of men and women and factors associated with accessibility to residential land

The analysis in Tab. 7 revealed significant relationships between the extracted factor scores (affordability, land availability, tenure security, and ease of transaction) and the socio-economic characteristics of male and female homeowners (age, income, educational qualification, occupation, and length of stay) in the study area. For male homeowners, correlations were predominantly positive. Affordability was significantly correlated with religion (r = .193), household size (r = .239), income (r = .313), and occupation (r = .205). Land availability showed significant positive correlations with educational qualification (r = .207) and occupation (r = .174). Tenure security was significantly associated with age (r = .392), occupation (r = .205), and length of stay (r = .340), while ease of transaction correlated positively with religion

(r = .287), household size (r = .254), and length of stay (r = .155).

Conversely, results for female homeowners revealed predominantly negative correlations, with the exception of length of stay. Affordability exhibited negative correlations with marital status (r = −.192), household size (r = −.235), and income (r = −.180), but a positive correlation with length of stay (r = .182). Land availability showed negative correlations with religion (r = −.397), marital status (r = −.208), household size (r = −.178), income (r = −.189), and educational qualification (r = −.355), but a positive correlation with length of stay (r = .208). Tenure security was negatively associated with occupation (r = −.276), while ease of transaction showed negative correlations with age (r = −.317), religion (r = −.355), marital status (r = −.313), household size (r = −.194), income (r = −.262), and occupation (r = −.268) at the 0.05 significance level.

The findings show that access-related land factors of male homeowners are positively influenced by socio-economic variables, while female homeowners experience predominantly negative associations, particularly with marital status, household size, and income, with the exception of longer residence duration, which enhances their access.

5. Discussion

Findings on the factors associated with access to land for residential development reveal that financial considerations, land availability, procedural issues, tenure security, and personal attributes were central to land access for housing development among men. Among women, financial considerations, land availability, tenure security, personal attributes, and procedural factors were identified based on their order of importance. Financial considerations emerged as the most influential factor for both men and women. This is largely because residential land typically goes to the highest bidder, and the urban poor often acquire land through informal channels. Land in the informal market is not regulated by government authorities, and prices are typically dictated by informal market forces. This finding aligns with the work of Babatunde (2014), who noted that residents often purchase land through informal markets. It also supports Nwuba et al. (2015), who asserted that land price significantly determines access to urban residential land. Furthermore, it corroborates Aluko et al. (2004), who observed that the cost of acquiring land in informal urban markets can be up to four times higher than in formal markets. Land availability was the second most important factor for both men and women. Access cannot occur without land being available, and limited availability undermines sustainable housing development in urban border areas. As previously established, informal institutions are the primary providers of residential land, particularly for the urban poor in border communities. Women assign greater importance to land availability, possibly due to limited access routes, cultural restrictions, or exclusion from inheritance. While men may navigate scarcity through formal transactions, women often depend on communal access or spousal/familial rights, making perceived availability more critical. This finding is consistent with Lawal and Adekunle (2018), who highlighted that an adequate supply of land is a prerequisite for sustainable housing delivery. Similarly, Oyedeji (2018) identified land availability as the second most influential factor, after affordability. Oyedeji (2018) further noted that increased land availability reduces competition and incidences of title forgery.

Procedural was the third factor among men, while tenure security was the third among women, suggesting gender-based differences in residential land access. The reason for this could be due to cultural issues, such as norms, customs, and traditions that tend to favour men in land acquisition. Procedural factors – including bureaucratic delays, complex registration processes, and high transaction costs – are major barriers for men. Men are often affected by bureaucratic hurdles such as documentation, titling, and institutional corruption – likely because they engage more directly with formal land acquisition systems. Women may not be affected by such procedures or access land through informal channels, where procedural issues are less pronounced. On the other hand, tenure security was more significant among women. Tenure security is a greater concern for women, reflecting social vulnerability and exclusion from legal land ownership in many traditional systems. Insecure tenure affects women in several ways: (1) they often lack confidence in their land rights, (2) they typically hold secondary rights that are not formally recognized, and (3) their rights are frequently not protected from forced eviction. Security of tenure and personal attributes were the fourth factor among men and women, respectively. Security of tenure affects land access among men due to informal market constraints, insecure tenure and title, stringent titling procedures, among others. This study corroborates the studies of Oladehinde et al. (2017), Aluko and Amidu (2006), and Ajayi and Adebayo (2017) in this regard. In contrast, personal attributes that affect women's land access could be due to the low socioeconomic status of women compared to men. Low socioeconomic status, such as low monthly income, informal employment, is more prevalent among women, limiting their ability to independently finance land acquisition. Consequently, many women depend on their husbands for land access. Personal attributes and procedures were the least factors hindering land access among men and women, respectively. While the literature (Oladehinde et al. 2023; Owoeye and Adedeji 2015; Omirin 2003; Adekola et al. 2013) has identified a variety of factors influencing

Tab. 7 Pearson correlation analysis of the relationship between personal characteristics and factors associated with residential land access for men and women.

		Male				Female			
		Afford-ability	Land availability	Tenure security	Ease of transaction	Afford-ability	Land availability	Tenure security	Ease of transaction
Age	Pearson correl.	.081	.068	.392**	−.057	−.126	−.095	.106	−.317**
	Sig. (2-tailed)	.259	.342	.000	.425	.104	.222	.176	.000
	N	196	196	196	196	166	166	166	166
Religion	Pearson correl.	.193**	−.058	−.080	.287**	.118	−.397**	−.037	−.355**
	Sig. (2-tailed)	.007	.422	.267	.000	.130	.000	.637	.000
	N	196	196	196	196	166	166	166	166
Marital status	Pearson correl.	.021	−.098	.027	.023	−.192**	−.208**	.094	−.313**
	Sig. (2-tailed)	.771	.170	.704	.750	.013	.007	.227	.000
	N	196	196	196	196	166	166	166	166
Household size	Pearson correl.	.239**	.127	.139	.254**	−.235**	−.178**	.026	−.194**
	Sig. (2-tailed)	.001	.075	.052	.000	.002	.022	.740	.012
	N	196	196	196	196	166	166	166	166
Monthly income	Pearson correl.	.313**	.086	.074	−.041	−.180**	−.189**	.059	−.262**
	Sig. (2-tailed)	.000	.231	.302	.566	.020	.015	.452	.001
	N	196	196	196	196	166	166	166	166
Educational qualification	Pearson correl.	.070	.207**	.037	.023	.083	−.355**	.102	−.142
	Sig. (2-tailed)	.329	.004	.609	.753	.286	.000	.191	.068
	N	196	196	196	196	166	166	166	166
Occupation	Pearson correl.	.205**	.174**	.205**	.139	.040	.021	−.276**	−.268**
	Sig. (2-tailed)	.004	.015	.004	.052	.612	.786	.000	.000
	N	196	196	196	196	166	166	166	166
Length of stay	Pearson correl.	.106	−.132	.340**	.155**	.182**	.208**	−.110	.046
	Sig. (2-tailed)	.138	.065	.000	.030	.019	.007	.159	.560
	N	196	196	196	196	166	166	166	166

** Correlation is significant at the 0.05 level (2-tailed).

land access, this study highlights that their importance varies by gender in the study area.

The study further reveals significant gender-based differences in how socio-economic characteristics influence access to residential land among male and female homeowners in the study area. For male homeowners, correlations between factor scores (affordability, land availability, tenure security, and ease of transaction) and socio-economic variables were predominantly positive, indicating that improvements in socio-economic status – such as higher income, better occupation, education, and longer residence – enhance men's capacity to secure land. For instance, affordability strongly correlated with income and occupation, suggesting that men with greater financial resources or better jobs are more able to afford land. Tenure security also increased with age and length of stay, reflecting the cumulative advantage men gain over time through social capital and familiarity with local land networks. In contrast, female homeowners displayed predominantly negative correlations, except for length of stay, which showed a positive relationship. For example, affordability was negatively correlated with marital status and household size, suggesting that women's access to affordable land decreases as household responsibilities and marital dynamics intensify. Similarly, land availability was negatively correlated with religion and education, implying that cultural and religious norms, rather than empowering women, often restrict their opportunities to acquire land even when they are educated. The negative correlations for income also suggest that increased earnings do not necessarily translate to improved land access for women, possibly due to entrenched gender biases in customary and informal land markets that prioritize male dominance.

These variations arise primarily from structural and cultural inequalities embedded in the land tenure systems of border communities. Men benefit from patriarchal norms that privilege male ownership and inheritance, enabling positive outcomes as their socio-economic status improves. Conversely,

women face systemic barriers such as customary laws, religious restrictions, and gendered social roles that constrain their land access regardless of improvements in income, education, or occupation. The only variable showing consistent positive effects for women is length of stay, highlighting the importance of social integration and long-term residency in gradually improving women's claims to land. This supports the assertions of Budlender et al. (2011) and Oladehinde et al. (2024), who observed that women often depend on their husbands to access land, making marriage a key mediating institution in secure access to residential land. This also agrees with the submission of Lawanson (2010), who noted that women's relative powerlessness both economically and politically in a typical African setting limits their control over resources, particularly residential land, and also that male superiority and dominance over resources in Nigeria originated from historically rooted culture and religion. These findings support earlier assertions by Ajayi and Adebayo (2017) and Adekola et al. (2013), who also noted that land access is affected by different factors, and these factors vary among men and women. The underlining causes of these variation between men and women according to Cotula and Mathieu (2008), Toulmin (2009), Oladehinde et al. (2024) could be attributed to difference in socio-cultural norms which make land in many Nigeria communities to be patrilineal; gendered roles and responsibilities which make women to be traditionally tasked with caregiving and domestic roles, limiting their participation in land transactions and men as family providers, legitimizing their land ownership in both customary and formal systems; and legal and institutional barriers which may not support women's land claims, due to lack of enforcement, gender-insensitive policies.

6. Conclusion and recommendations

The study has investigated the factors influencing access to residential land in urban border communities of Imeko Afon Local Government Area, Ogun State, Nigeria, through a gendered lens. The findings reveal that a greater proportion of female respondents experience insecure access to land compared to their male counterparts, indicating that women are more land-insecure than men. This disparity has significant implications for sustainable housing development for both genders. The study showed that shared and distinct factors affected men and women in accessing land for housing development. Affordability and land availability were universal barriers, while procedural, tenure and personal factors affect men and women differently. Addressing these gendered differences is essential for equitable, inclusive housing and land development policies. It was observed through the use of binary probit regression that access to residential land is significantly influenced by the extracted factor scores of men and women in urban border communities. For men, lower levels of affordability, limited land availability, and weaker socioeconomic status tend to reduce their likelihood of access to residential land, while improvements in tenure security and procedural conditions often increase the probability of land access among men. In contrast, limited land availability and bureaucratic barriers tend to reduce the likelihood of access, while increase in financial capacity, tenure security, and stronger socioeconomic status enhance women's access to residential land. It was established from Pearson correlation that socioeconomic characteristics of men influence access to residential land, while women's access is shaped differently, with some key socioeconomic variables negatively affecting their ability to access land. Socioeconomic status of women sometimes may not guarantee land rights due to systemic, cultural, and institutional barriers. The study concluded that access to land for residential development is influenced by different factors, and these factors significantly influence the level of access among men and women. These factors make residential land physically unavailable due to high cost, insecure tenure, procedural, and personal issues.

While this study provides valuable insights into the gendered dimensions of land accessibility in urban border communities, further research is necessary. Future studies should incorporate additional variables to better understand the dynamics of land access for residential development. Comparative studies across international border communities in sub-Saharan Africa are particularly recommended, as the factors influencing land access in West Africa may differ from those in other regions due to variations in cultural norms, political systems, and geographic contexts.

Despite these limitations, the findings of this study contribute meaningfully to the existing literature and offer practical implications for policy and sustainable housing development. First, the study underscores the need for gender equity in residential land access. Differences in socioeconomic status of men and women may further increase the disparity in their land access. Efforts should be made to start gender-based empowerment programs that will increase job prospects and enhance the quality of life for urban residents. Second, the study can help to inform policy implementation around the issues of access to land for residential development, not only in urban border region of Nigeria but also in urban border regions of other developing countries in support of SDGs 1 and 5 for reducing poverty and ensuring gender equality regarding rights and control over land resource. These initiatives should take into consideration the factors of affordability, availability, security of tenure, procedural, and personal attributes. In addition to this are the deep-rooted customs and traditions in the

border regions of Nigeria that increase discrimination against women. Gender based policies and programs that address the problems of land accessibility (such as tenure insecurity, lack of land title, bureaucratic delay, difficulty in the land registration procedure, insecure land rights, high cost of transaction, among others), especially among low-income men and women, should be formulated and implemented. This will further help in ensuring that land law guarantees equitable land management in protecting the rights of vulnerable men and women in the study area.

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Kosovo tourism in the shadow of geopolitical change

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ABSTRACT
This article employs a mixed-method approach – combining a literature review, descriptive statistical analysis, correlation testing, and the GIS for data visualization – to analyze the effects of geopolitical changes and political instability on tourism in Kosovo. Given Kosovo's goal of establishing tourism as a leading economic sector, the aim of this article is to determine whether and to what extent geopolitical factors influence its development. Despite persistent regional tensions and limited international recognition, Kosovo's tourism has remained resilient and shown gradual growth, primarily driven by diaspora and regional visitors. The findings reveal no statistically significant correlation between annual geopolitical events and tourist arrivals, indicating that the tourism industry has adapted to low-level instability. The study highlights a potential for sustained tourism growth in Kosovo in the future.

KEYWORDS
geopolitics; tourism development; Kosovo; political instability; post-conflict recovery

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1. Introduction

Global security environment is facing social, economic and environmental issues such as transnational crime, extremist groups, cyber security, energy security, climate changes, environmental pollution, and the spread of infectious diseases.

Theoretical approaches within this topic in general deal with the interdependence of security and tourist arrivals, impact of terrorism on tourism, the recovery of tourist destinations after post-terrorist attacks, the role of the rule of law in tourism countries, etc. In that aspect paper of Yan and Yungang (2024) gives a critical review of the emerging field of *tourism geopolitics*. These authors advocate that tourism and geopolitics are intrinsically interwoven but are not sufficiently theorized. Their main idea is that tourism influences and it is the result of geopolitical processes. According to their opinion a deeper integration of tourism and political geography through interdisciplinary frameworks is necessary.

Hall's stand (2017) is that geopolitics has not been a significant topic in tourism studies, but nevertheless critical shift in geopolitics in relation to tourism happened. He highlights the issue of identity, which is increasingly under pressure of programmed developments influence, neoliberal policies and the growing market. In addition to this topic, critical geopolitical perspectives are also related to security and tourism as well as hospitality. Tourism and hospitality have emerged in critical geopolitics although it has not had a significant influence on the literature that appears in tourism journals. These issues are significant for the relationships between geopolitics and tourism because they reflect the ways in which research debates are shaped by geopolitical forces (Hall 2017, 9).

In that symbiosis of geopolitics and tourism, tourists choose locations and destinations characterized by economic, political and social security. In fact, tourists are more willing to pay more to be sure that they are visiting a safe destination. Albeit geopolitical risks are reduced they can be harmful to tourism as an economic sector and overall economic growth and development in the short, medium and long term. Kosovo is one of many countries characterized by numerous political, social and economic turbulences. The most important are the bilateral disputes between Kosovo and Serbia that affect regional destabilization. All this has a negative impact on security in the country. Meantime, the possibility of a military attack on the sovereignty and territorial integrity of the Republic of Kosovo is small, primarily due to the presence of NATO (KFOR) and the increase in the protective capacities of the Kosovo Security Forces. Nevertheless, the global and regional security environment requires such a threat to be constantly assessed and considered (Kosovo Security Strategy 2022–2027). Limited effect when considering geopolitical situation in Kosovo is that Kosovo is not universally recognized as a sovereign state (not a UN member). Kosovo international legitimacy was contested from the moment of its birth (Surroi 2011). This fact has impact on tourism through visa restrictions for some travelers, while flight and travel infrastructure are limited due to the lack of airspace access or international aviation agreements and travel advisories from countries that don't recognize Kosovo may discourage visits. As for perception, many tourists are uncertain about safety, legality, or entry conditions. As a result, tourism grows more through diaspora, niche travelers, and regional tourism than mainstream global flows. Besides, due to its young statehood and conflict-related damage, Kosovo has limited infrastructure, which impacts tourism.

Yet there are advantages of geopolitical position of Kosovo in Europe as EU helps develop infrastructure and promote Kosovo abroad. The European integration process is crucial for Kosovo's political stability, economic prosperity, and social development (Tare 2023). Positive is Kosovo's aspiration for EU membership and involvement in EU-facilitated negotiations which plays a stabilizing role (The EU and Kosovo 2021). They include rich cultural heritage, such as UNESCO-listed medieval monasteries and Ottoman-era architecture, excellent opportunities for cross-border cooperation with Albania, North Macedonia and Montenegro, which all can influence adventure and historical tourism, but dark tourism too. Considering the close connection between geopolitical events and tourism, and their intertwining, the aim of this paper is to determine whether and to what extent geopolitical factors influence tourism development.

Accordingly, this study addresses the following research questions:

1. Is Kosovo still perceived as an unsafe tourist destination even 15 years after its independence?
2. Are the positive geopolitical events most important for Kosovo's rise as tourist destination?
3. Why is Kosovo lagging behind in the development of tourism capacities and the number of foreign tourists compared to neighbouring countries?

2. Theoretical framework

This paper analysis broader context of interconnection of geopolitical situation and tourism development in The Republic of Kosovo (later in the text only Kosovo). It will take into consideration geopolitical threats which have a great impact on security perception of a tourist destination, in this case Kosovo. Most published papers dealing with this topic are in the focus of interest of scientists concentrating on tourism or interconnection of tourism and politics, while not many (geo)political papers tackle this issue. Tourism in many countries contributes to rising aggregate

domestic prosperity and creating new job opportunities, especially where conventional economic activities are in decline (Kürşad Özlen and Poturak 2013).

There are challenges to developing tourism in a transitional context, particularly when transition is in the background of conflicts and wars as it is confronted with political instability (Reka 2017). Post-war, countries attempt to (re)create an image, but the effects of war on a country reiterate to the international community a sense of fear, and one would likely not imagine these countries as desirable tourist destinations (Wise 2011). Bosnia and Herzegovina and Croatia make a good example due to their simultaneous histories of conflict (Wise 2011) and comparison because of similarities with Kosovo.

As in Bosnia and Herzegovina or Croatia, tourism in Kosovo suffered due to the war events. Kürşad Özlen and Poturak (2013) stated that even though as Bosnia and Herzegovina has an exceptional tourism potential, tourism image has not been built in a way that would be recognizable on the international tourism market. It is the same case with Kosovo. In Bosnia and Herzegovina, it took several years (after the end of the war in 1995) for tourism to recover, hampered by ethnic tensions and the slow normalization of relations. Bosnia still struggles with fragmented governance but has growing eco- and adventure tourism. Through tourism projects it appears easier to address the lack of trust as the "politics" behind tourism are natural resources. Building up trust between people is the most important segment in developing tourism (Causevic 2010).

Although it has no direct border with Kosovo, the instability in the region which resulted in NATO bombing of Serbia (in 1999) at the time influenced the Croatian economy to a large extent, tourism in particular. The conflict captured international attention. The following tourist season, 2000, in which the Kosovo–Serbia conflict ceased and 12 months after the NATO bombing, the number of tourist arrivals and overnight stays not only surpassed the level of 1999, but overshot the level of 1998, resulting in an annual increase in overnight stays amounting up to 12.057 mil. (Tkalec and Žilić 2017). Therefore, tourism recovery in Croatia proceeded much faster, which was the consequence of the construction of infrastructure (a modern highway connecting Croatia, but also other neighboring countries with the coast), integration processes, primarily Croatia's gradual rapprochement with the EU, and stronger economic growth. Croatian tourism benefited a lot when joining EU in 2013 and since then it has completely recovered.

Kosovo, similar to Bosnia and Herzegovina, experienced a decline in tourism immediately after the war due to ethnic violence and tensions, and it took several years for tourism to take off. One of the causes of tourism decline was certainly insufficient infrastructure, both transport and tourist. Nowadays, EU-mediated dialogue has helped boost perception and tourism growth in Kosovo. Growth after 2014 likely reflects better infrastructure, marketing, and diaspora-driven visits. Many post-conflict countries first see a rise in tourism from diaspora returning or adventure/historical tourists. In Kosovo, there is a significant diaspora from Germany, Switzerland, and Nordic countries (Salopiata 2023). Many early tourists were returnees. Similar situation is recorded in Bosnia and Herzegovina and in Croatia.

Yet, the fact is that the unresolved question of Kosovo's status has considerable repercussions for the stability of Kosovo itself, and of the Western Balkans as a whole: as long as Kosovo's international legitimacy as a state is in question, its borders are not inviolable, which carries the risk of future armed conflicts that would affect the entire region. According to Gelbman (2022) border disputes and weapon rattling cause concern. Many tourists assess risk by proximity – as long as the main tourist sites are unaffected, tourism may continue.

As for political protests and unrest, there is usually mild to moderate drop, depending on the scale and media coverage. That means the media often play a key role in today's conflicts and become their integral part (Riznaj 2018). In Kosovo they likely had limited impact due to their scale and geographic focus. In this context, perception plays the key role because protests in tourist areas are more damaging than unrest in peripheral zones.

2.1 Some general thoughts on political instability and safety as geopolitical factors

According to Iaquinto et al. (2024) *tourism-geopolitics* interconnections, underscore how tourism and global politics are deeply intertwined. Their opinion is that travel as well as consumption, become expressions of geopolitical negotiation. Today events as simple as pop stars concerts (like Taylor Swift) can cause diplomatic tensions and raise questions about economic sovereignty, competition and soft power. In such cases tourism can become geopolitical instrument that shapes diplomatic relations, imaginative geographies, as well as identities.

Therefore the world has become more integrated and interdependent than ever before, and research shows that a tourism crisis in one region can have serious consequences on other locations. Due to the so-called *spillover effect*, tourist destinations can be negatively affected by adverse events in nearby areas, so it is logical for tourists to choose safer destinations (Bayar et al. 2023).

One of the forms of geopolitical risks are political factors which are predominant in a certain country. Political factors consist of the laws, regulations and governmental policies that facilitate or hinder direct marketing and influence tourism industry so they can create advantages and opportunities for it (Singh 2020).

For example, terrorism or the occurrence of corruption can strongly affect tourism sector. Corruption is a constant in every society and despite that, there is very little research focused on the interconnection between corruption and tourism. Higher levels of the rule of law can influence tourism through several aspects, such as institutional quality, enforcement of contracts, property rights protection, and the reliability of courts and the police (Gozgor et al. 2019 in Bayar et al. 2023). In Kosovo, political interferences and corruption in judiciary institutions and other public administrations have been condemned by the people and international organization rapporteurs for obstructing political progress (Reka 2017).

In addition to the corruption mentioned above, tourism in many countries declines when faced with various political instabilities that hinder its development. That means the political instability and war can increase the perception of risk at a destination and generate negative publicity, resulting in an inevitable decrease in tourist arrivals. Perceptions of risk can influence tourist decisions, and tourist destinations can be seriously affected. Policymakers in countries with strong tourism need to be aware of how such political instability is experienced (Ryu 2005).

In the contemporary political period, but also in the past two and a half decades, we have witnessed the resurgence of state power to enclose territories, (re) impose borders, and restrict the movement of certain categories of people (Scuzzarello and Kinnvall 2013 in Bianchi et al. 2020). Borders are no longer open. They are often closed depending on the situation and who wants to cross them. That way they become an additional factor in the interrelationship between geopolitics and tourism (Bainchi et al. 2020). Terrorist acts have accelerated this decision.

Terrorism is one of the biggest threats for tourism. An important fact for the international terrorism is that the actors (and/or sponsors) of a terrorist act are of a different nationality than of the country where they operate, therefore the identification of victims according to their nationality is one of the criteria for this kind of terrorism (Liu and Pratt 2017).

Tourism can be used as a tool for political and ideological goals and on the other hand, can be molded by political purpose, but the manipulation of tourism may result in disadvantage to it (Ryu 2005). (Geo) political environment impacts tourism industry in any country no matter the size. Whether this industry is large or small, political factors will always have an impact on it (Singh 2020). For example, the political implications of tourism mobilities between national territories demand deeper attention. Terrorism is in addition one of the most significant and constant geopolitical risks for tourism.

In Europe terrorism has been a constant threat for European citizens for more than a decade. Terrorism and political instability are the most feared risks for tourists (Seabra et al. 2019). According to the Europol report from 2023 "terrorism continued to pose a serious threat to EU Member States". Terrorism was still a major threat in 2022. At that time, around 28 terrorist attacks (completed, failed, or attempted) were carried out in Europe (according to the Europol report) and 380 people were arrested. Regarding the threat of terrorism in Europe, according to the Europol report from 2024, 426 people were arrested for terrorist crimes. The majority of these were related to jihadist terrorism (334). Most of them were carried out in Spain, France, Belgium, Germany, and Italy. There were likewise attacks related to leftist and anarchist activities (a total of 30) and ethno-nationalist and separatist activities (25). 120 terrorist actions were carried out in 2023, which is more than in 2022 (Europol 2024).

On the other hand, according to *Global Safety Report* from 2024, on a global level, people felt safer in 2023 than they did a decade ago. Regionally, at least seven in 10 people felt safe in Western Europe. Scores on the *Law and order index* are highly related to traditional development indicators, including global income, health, food security and homicide metrics. The index score for the world in 2023 was 81 out of a possible 100 – and in Kosovo 91! (Gallup 2024).

There is a clear connection between terrorism and tourism i.e. terrorism effects tourism in the most negative way. The perceived risk of terrorism will influence tourists' decision-making, regardless of their country of origin or their cultural background (Seabra et al. 2019). These changes in tourists' decision-making are largely due to the so-called memory effect. The memory effect refers to any feeling, anxiety or panic that leads individuals to change their usual behaviour (Shin 2017 in Seabra et al. 2019).

Covid-19 pandemic was yet another instability factor on geopolitical and global level. In their text Lučev and Zorko (2023) point out that the pandemic showed the vulnerability of the globalized world and once more emphasized the importance of borders and territories. In these new circumstances they become symbols of security redo. Through the concept of "geopolitics of fear", the ways in which spaces are marked as safe or unsafe are analyzed, which also affected tourist patterns.

3. Materials and methods

Analyzing relations between geopolitics and tourism, the Republic of Kosovo is a good example given that it is a state with numerous geopolitical challenges. In this research, in order to determine the perception of Kosovo as a tourist destination, more recent political-geographical events that could directly affect the stronger development of tourism were analyzed. This study employs a mixed-method approach combining a literature review, descriptive statistical analysis, and correlation testing. Basis for the literature overview were papers in *Web of Science Core Collection*

published by the authors who wrote on similar issues. A search was conducted to find out how the topic relating geopolitics and tourism in Kosovo is represented in scientific literature. In order to find out how many publications have been written, three key words were chosen according to the topic in the WoS databases (Web of Science Core Collection, Citation Index, Current Contents Connect, Data Citation Index etc.). The key words were geopolitics, tourism and Kosovo. According to the obtained results there are only 2 matching documents i.e., two publications selected from all databases. Both were in the categories Geography, Hospitality, Leisure, Sport&Tourism. The second search that was conducted included the same keywords, but this time in the category Title. No publications with the specified keywords were found in that search. This means that the problem is under-researched.

Analyzing literature it is obvious that political geographers in general discuss broader geopolitical issues, for example how the state tries to use tourism as a type of soft power to facilitate or prevent (cross-border) tourist mobility, thereby mediating interstate relations (An, Dittmer 2023).

As for data collection, statistical data on the international tourist arrivals in Kosovo from 2008 to 2023 were obtained from the Kosovo Agency of Statistics (KAS), Eurostat, and the OECD. Each year in this period was associated with a major geopolitical development that potentially affected tourism flows. This resulted in the table which synthesizes the temporal alignment between key geopolitical events and annual tourist arrivals, serving as the empirical foundation for the correlation analysis discussed in the results section.

Data analysis was based on geopolitical events which marked the chosen period and to quantify these dynamics, each geopolitical event was classified as follows:

- Positive (+1): periods of political stability, normalization agreements, or EU-facilitated dialogue, periods without ethnic tensions, political agreements, etc.
- Negative (−1): incidents of border unrest, violent clashes, ethnic conflicts, attacks on peacekeeping missions, diplomatic tensions etc. or
- Neutral (0): years with mixed developments or external disruptions (e.g., COVID pandemic).

Therefore, each year is scored qualitatively (based on the event type), and then the scores are quantitatively correlated with the number of tourists in order to see how stability/instability affects tourism flows. A Pearson Correlation Coefficient is applied to assess the relationship between geopolitical event scores and annual tourist arrivals. In this case the pandemic years (2019–2020) are excluded. The used method bridges qualitative and quantitative analysis because it converts complex political contexts into analyzable data. Besides, it shows how tourism responds to shifts in political stability over time and reflects the tinged post-conflict society like Kosovo. There, even the smallest progress or tensions can strongly influence perception.

4. Some tourist indicators for Kosovo and other Western Balkans countries

In the period after the war in Kosovo, tourism had an important place in economic activation of the country.

Tab. 1 Number of foreign and local visitors in Kosovo according to region between 2008 and 2023 (in percentage).

Year	Gjakovë	Gjilan	Mitrovicë	Pejë	Prizren	Prishtinë	Ferizaj	Total
2023	14.08	34.44	21.49	22.75	24.19	11.75	22.87	18.23
2022	5.70	13.22	17.21	10.95	16.73	12.78	18.29	13.51
2021	5.14	9.95	16.82	10.73	12.50	8.99	10.94	10.42
2020	1.73	2.33	7.50	6.14	4.75	3.73	1.79	4.36
2019	8.64	7.24	8.67	9.63	8.93	8.20	5.50	8.42
2018	15.70	7.32	7.78	11.11	8.50	7.63	5.67	8.83
2017	14.66	5.05	5.28	8.48	7.31	7.21	5.51	7.37
2016	17.48	5.62	3.95	9.03	7.75	7.32	4.20	7.55
2015	2.45	1.39	1.24	3.21	2.64	5.96	2.83	4.09
2014	2.23	1.32	1.45	1.71	1.40	5.16	1.93	3.16
2013	1.64	1.46	1.60	0.98	1.31	4.60	2.68	2.80
2012	1.73	1.65	1.58	1.12	1.01	4.59	4.56	2.90
2011	1.77	1.92	1.45	0.98	0.88	3.12	3.26	2.12
2010	2.20	1.68	1.59	1.23	0.76	3.29	4.54	2.32
2009	2.42	2.73	1.36	1.23	0.75	3.85	4.80	2.61
2008	2.45	2.68	1.03	0.73	0.59	1.81	0.63	1.30

Source: Kosovo Agency of Statistic, Tourism and Hotels – Yearly indicators, 2008–2023.

Today participation of the tourist economy in GDP is currently estimated to be 6–7%, while in the 1970–1999 period, it rated from 1.9 up to 2.3%. The growth of the tourist economy in the GDP results is the sharp decline in economic activity in social and public sectors of the economy. As already mentioned, the largest importance and relevance to the development of tourism in Kosovo stands in political, economic and security reasons (Nimani and Zeqiraj 2019).

Kosovo offers good opportunities for several types of tourism such as winter tourism, cultural tourism, hiking, recreational sports etc. as well as excellent potential for mountain tourism (the mountain of Prokletija and Shar Mountain). But it is noticed that the hotels are concentrated in the areas that have nothing to offer in terms of tourism, urban centers and the most important infrastructure, such as roads (Džogović and Koteski 2018). Kosovo has a road network consisting of 630 km of main roads. In addition, there are two highways: Prishtina – Hani and Elezit, which connects Kosovo with North Macedonia; and Prishtina–Morina, which connects Kosovo with Albania (Kosovo Tourism Strategy 2024–2030).

Meanwhile, geopolitical events mentioned above haven't had much influence on tourism in Kosovo in the last 15 years. According to numbers (Tab. 1), in 2023 there was a significant increase in tourist arrivals in comparison to 2008 with some exceptions for the years 2011, 2013 and 2017 as well as pandemic years 2019 and 2020. In 2023, in comparison to 2008 there was half a million (577 192) tourist more.

The regions that dominate with the most accommodation units are Prishtina, Peja and Prizren. The rate of utilization in accommodation capacities, according to the KAS, is around 12–15%, except for the period 2019–2021 where, due to the pandemic, this rate dropped significantly (Kosovo Tourism Strategy 2024–2030).

The fact is that the number of foreign tourists (Fig. 1, Fig. 2) is the largest in the most attractive cities/regions like Prishtine, Prizren and Gjakove which can offer much more as tourist destinations than some other cities in Kosovo. Prishtine is the most visited due to the fact it is the capital city and the center of economy, culture and international presence. It has constant rise of tourist arrivals with the highest share of tourists in recent years (2021–2023). Furthermore, the presence of about half a million people living in the municipality of Pristina provides a great opportunity to develop local production and farmer-to-consumer marketing (Sallahu 2022). Prizren is one of the historically most popular destinations with a steady growth up to 24.19% in 2023. It's known for its historic and cultural value, which aligns with its increasing

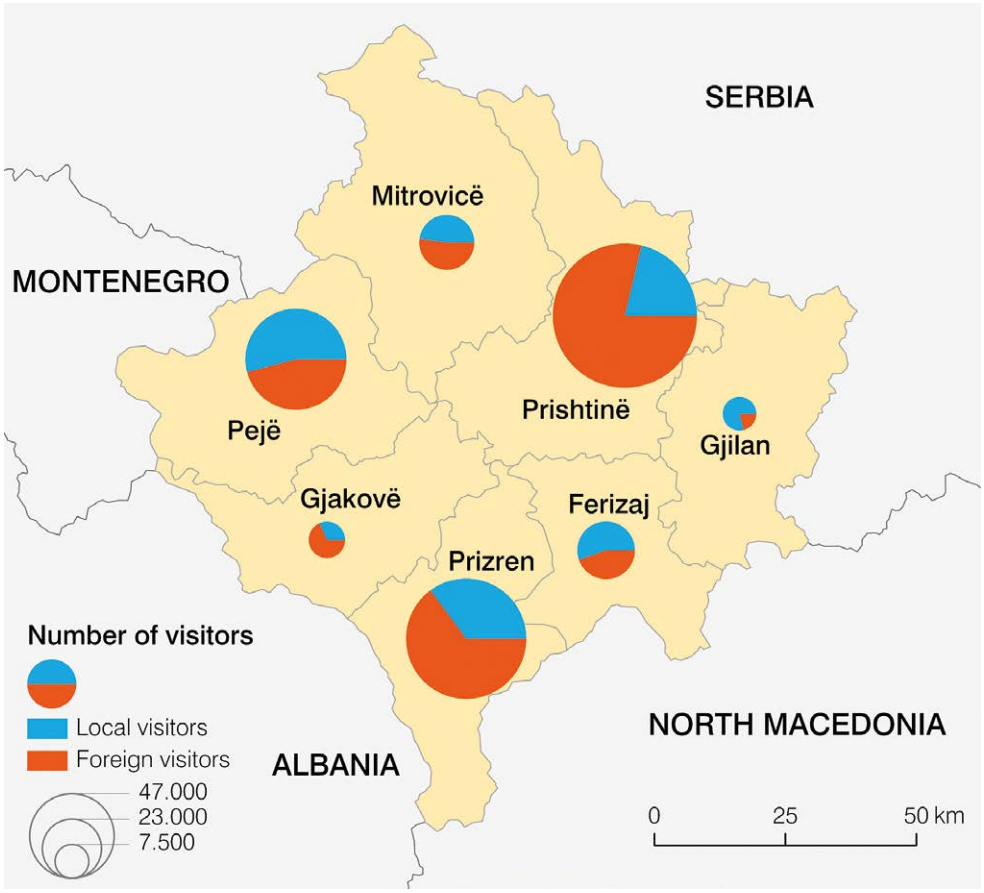

Fig. 1 Number of foreign and domestic visitors in Kosovo by region in 2023.

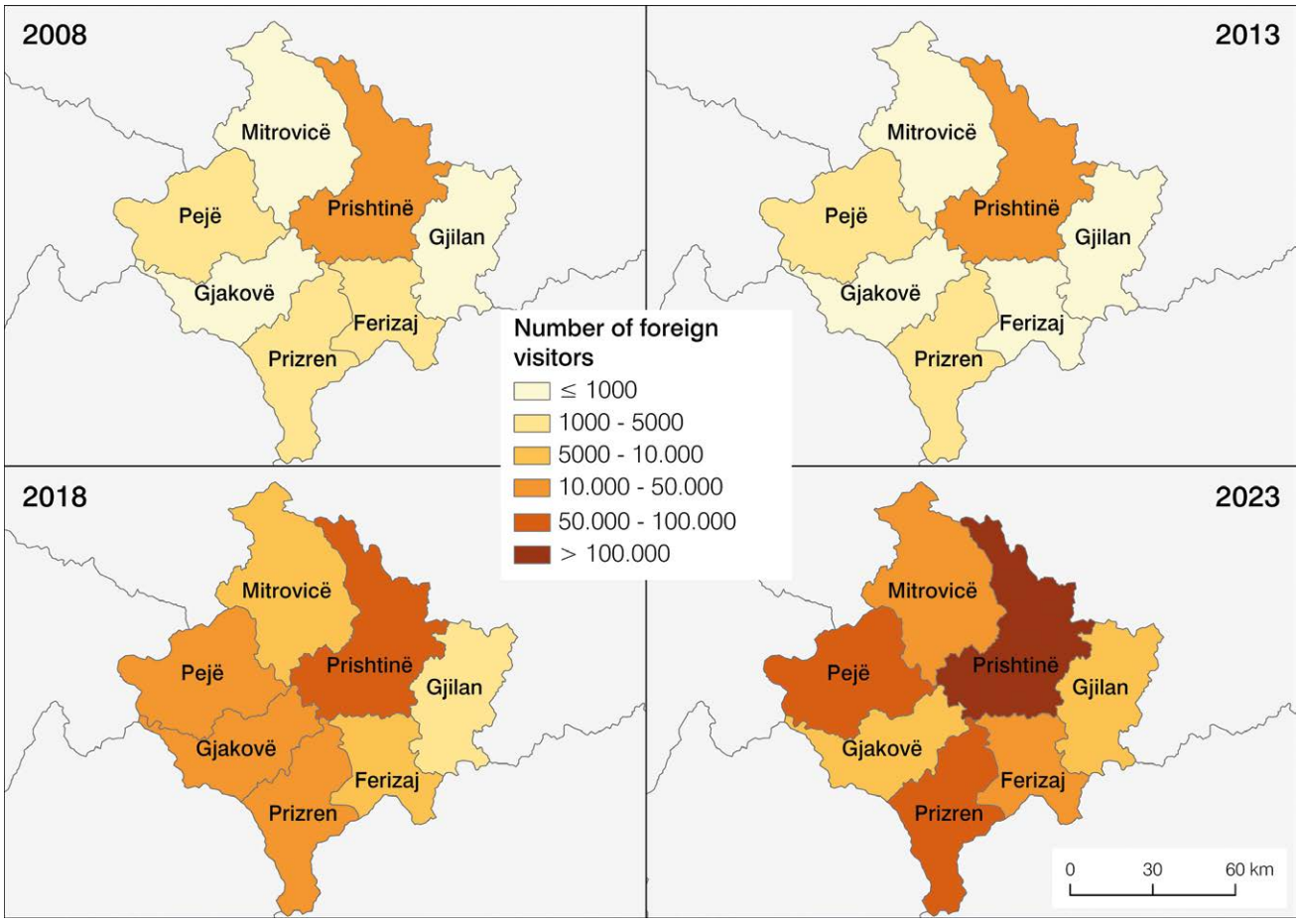

Fig. 2 Number of foreign visitors in Kosovo by region in 2008, 2013, 2018 and 2023.

popularity (KEA European Affairs 2020). On the other hand, in certain regions, this number is often much smaller in comparison to local visitors. This is the case in Gjilan, Mitrovicë, Ferizaj and Peje. Regions such as Gjilan and Mitrovicë show more fluctuations in the average stays, typically having lower averages compared to Prizren and Peja. These fluctuations could be due to less developed tourism infrastructure or fewer high-profile tourist attractions.Yet, these regions present opportunities for growth through targeted tourism development and marketing strategies (Torres et al. 2024). Nonetheless, Gjilan has lately had a significant growth, which may reflect new tourism initiatives, or border-related transit tourism, while Ferizaj has also had a consistent rise, especially after 2020, which could signal stronger regional tourism development, possibly including natural attractions or retail/tourism hubs. Peje had a gradual increase from 0.73% (2008) to 22.75% (2023) which is likely tied to Accursed Mountain and adventure tourism. All in all, Kosovo's regional tourism has diversified significantly since 2008. The overall average percentages per region increased over time, reflecting a significant growth in total tourism post-2015 (especially after the pandemic decline in 2020).

It is necessary to compare Kosovo with other Western Balkans countries, in the aspect of tourism too. (Western) Balkans is a competitive destination both for its residents and the rest of the visitors. A growth trend in all volume numbers of tourists and their overnights is showcased until the 2019 pandemic outburst, as a progression and from 2019–2021 the volume number diminished due to COVID-19 and movement restrictions (Baratsas 2024). Between 2020 and 2021 all the Western Balkans recorded a sharp increase in the number of non-resident tourists (Tab. 2) arriving at hotels and similar establishments. Kosovo, as all other countries recorded more than 100% rise. A trend of growth of the number of arrivals by 113% in Kosovo happened between 2020 and 2021. The number of non-residents arrivals had been growing from year to year. The sharp falls in arrivals from 2019 to 2020, a direct effect of the Covid-19 pandemic through the restrictions imposed on travelling and accommodation of tourists and other travelers, can be clearly seen for Kosovo. Accordingly, there was a sharp fall in tourist arrivals in Kosovo (−52%) (Eurostat 2024). Tourism in the region has generally continued a positive post-pandemic recovery, with limited impact by Russian and Ukrainian

Tab. 2 Number of arrivals of non-residents staying in hotels and similar accommodation establishments, 2008–2021 (thousands).

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
EU-27	206 852	194 613	208 787	224 365	229 789	:	251 284	265 146	275 486	295 898	306 924	316 383	83 261	112 146
MN	492	437	471	499	533	581	557	595	669	795	913	:	:	:
NM	214	220	231	301	324	373	392	456	489	601	674	725	115	284
A	:	:	:	:	:	:	:	:	:	:	691	736	281	656
S (1)	561	567	618	683	707	767	880	1013	1147	1336	1514	:	392	776
BH (2)	315	304	359	386	424	510	511	640	731	870	994	1139	189	485
K (3,4)	**25**	**36**	**34**	**30**	**49**	**50**	**61**	**79**	**164**	**162**	**193**	**177**	**85**	**181**

MN – Montenegro; NM – North Macedonia, A – Albania, S – Serbia, BH – Bosnia and Herzegovina, K – Kosovo; (:) not available; (1) 2012: break in series; (2) Tourism and municipality licensed accommodation establishments; Data supplied by and under the responsibility if the national authorities; (3) 2016: break in series; 2021 provisional.
Source: Eurostat (2020): Statistics on tourism for the enlargement countries 2020 edition, Luxembourg: Publications Office of the European Union, 2020; Eurostat (online data code:tour_occ_arnat) and Eurostat collection.

tourists over 2021 and 2022. Specifically, tourism has continued to increase since COVID-19 in Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia, but not so much in Albania and Kosovo. Moreover, the post-pandemic recovery was marked by a divergence of performance between the more manufacturing-oriented economies (Serbia, Bosnia and Herzegovina, and North Macedonia) and the relatively more services-oriented and tourism-dependent economies (Albania, Montenegro and Kosovo) (OECD 2024).

According to data, between 2008–2011, during the immediate aftermath of Kosovo's declaration of independence and ongoing tensions tourism numbers increased slightly or remained stable. This suggests that political instability and violence had a short-term negative impact on tourism**.** Between 2012 and 2015, as Serbia and Kosovo began EU-mediated dialogue and signed normalization agreements, tourism numbers rebounded strongly. As for border tensions (2011, 2017), they led to localized and mild tourism declines but didn't prevent long-term growth.

Serbia had the largest number of arrivals of non-residents staying in hotels and similar accommodation establishments, around 1.5 million, followed by Montenegro and Bosnia and Herzegovina. Kosovo, through all the years had convincingly the lowest numbers. These figures can be compared with a total of 306.9 million arrivals of non-residents at hotels and similar accommodation establishments in the EU-27 in 2018. Unfortunately, there is no data available for Albania for that period, only after 2018. In that context, Albania had the second-best results in the period from 2019 to 2021, just after Serbia.

Kosovo can offer tourism in the mountain regions, in addition to sites of historical and cultural interest, thus offering a wide range of tourism types., But the relative capacity of bed places is at a lower level in Kosovo. In comparison to other Western Balkan countries, Kosovo has the smallest number of beds, but it grew over the analyzed period (between 2018 and 2023). The largest increase in the number of beds is mostly recorded in the capital Prishtina, followed by Prizreni and Peja (Fig. 3).

When analyzing some other countries in the Western Balkans in the period from 2011 to 2021, the largest capacity of bed places in hotels and similar

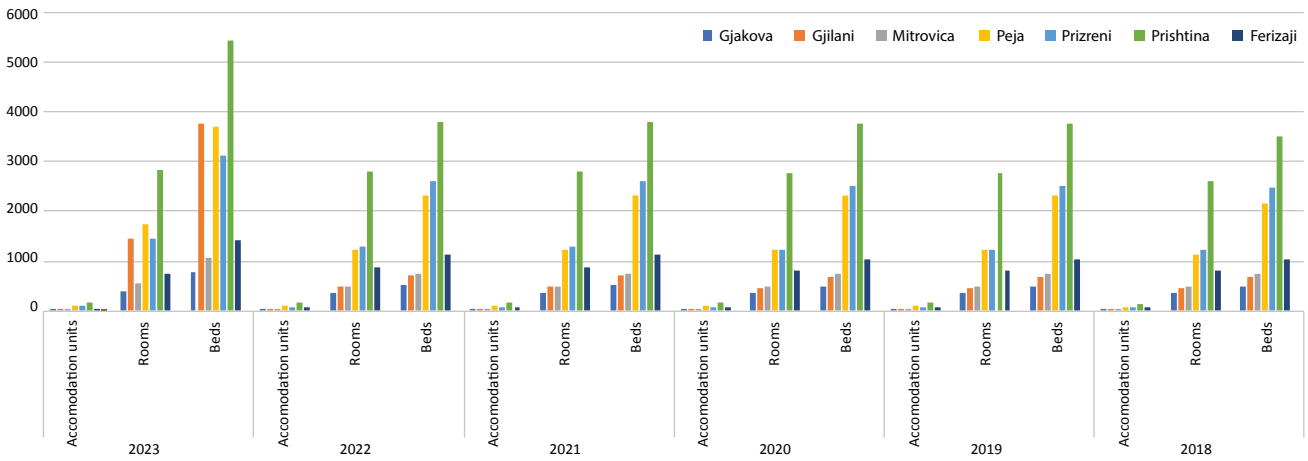

Fig. 3 Hotel capacities in Kosovo by region, 2018–2023.
Source: Kosovo Agency of Statistic, Tourism and Hotels – Yearly indicators, 2008–2023.

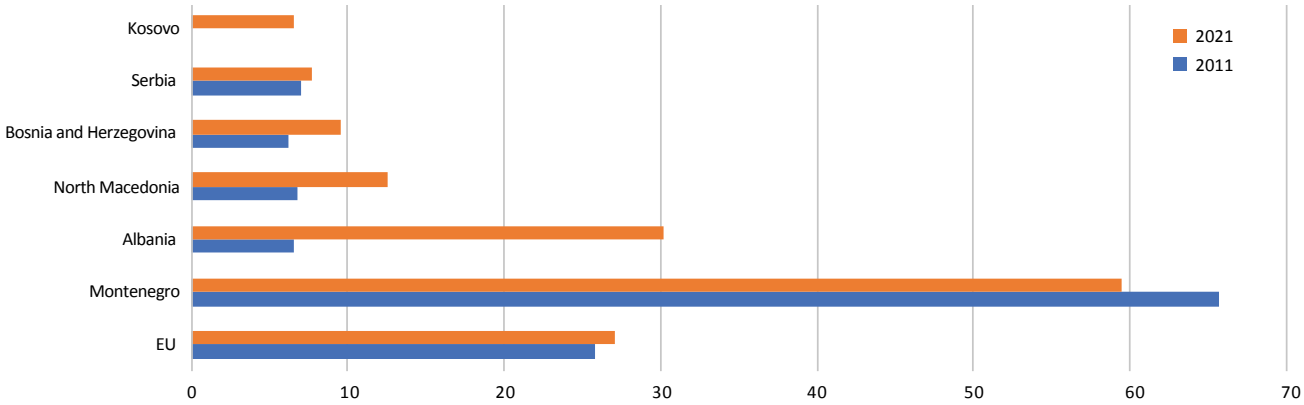

Fig. 4 Bed place capacity in hotels and similar establishments in Western Balkans and EU, 2011 and 2021 (bed places per thousand inhabitants).
*Data for Kosovo available from 2016.
Source: Eurostat (online data codes: tour_cap_nat and demo_gind) and Eurostat data collection.

establishments for example in 2021, was found in Albania with 85 000 bed places, and the second highest in Serbia (53 000). The capacity of bed places was at the similar level in Bosnia and Herzegovina (33 000) and North Macedonia (24 000), with Kosovo at around half of this level (less than 12 000). North Macedonia was the only country to experience an increase in the number of bed places for each year of this period. All the other countries experienced years in which the number of bed places declined, particularly in the early years of this period. The number of bed places offered especially decreased compared to the previous year in both 2012 and 2013 in Albania; the same applies to Bosnia and Herzegovina in 2012 (Fig. 4) (Eurostat 2023).

The next category of data shows how many tourist beds there were per square kilometer in the period 2008–2018, in the Western Balkan countries (Tab. 3), which additionally shows the tourist density in the analyzed countries, as well as the level of development of Kosovo's tourism (in this selected segment) for this period. Data for Albania, unfortunately, is not available for this period.

According to the obtained data, although the number of tourist beds is not available for a large part of the analyzed period, it is evident that from 2016 to 2021, Kosovo was one of the leading countries in the Western Balkans in terms of the density of tourist beds per square kilometer, just after Montenegro (between 2.5 and 3 beds per km^2). Still, these are modest capacities, with a mix of hotels (47%) and motels (36%), which means that Kosovo's accommodation capacity is comparatively lower than its neighbors, indicating potential for development in its tourism infrastructure.

According to Kosovo Tourism Strategy 2024–2030, the register of accommodation capacities on the territory of Kosovo contains 490 units, which are functional and carry out hotel activities in the country. The country's strategic focus on enhancing its tourism sector could lead to growth in accommodation offerings which can influence number in overnight stays in the coming years in comparison to current data (Fig. 5).

We can conclude based on the presented data, that the economy of Kosovo could be much more oriented towards tourism in the future, which is necessary for its further development. It should be oriented towards the launch of well-known tourist centers, especially those in the process of privatization. Strategic planning for the development of tourism in Kosovo should be focused on macroeconomic stability, and the reduction of unemployment, but generally promoting economic development (Nimani, Zeqiraj, 2019).

Tab. 3 Number of tourist beds per km in Kosovo and other Western Balkan countries from 2008 to 2018.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Montenegro	2,96	3,04	2,46	2,53	2,53	2,38	2,46	2,31	2,53	2,60	2,60
N. Macedonia	0,42	0,46	0,50	0,54	0,58	0,62	0,66	0,70	0,77	0,81	0,89
Albania	:	:	:	:	:	:	:	:	:	:	:
Serbia	0,65	0,67	0,72	0,69	0,65	0,72	0,69	0,67	0,67	0,67	0,68
Bosnia and Herzegovina	0,42	0,44	0,46	0,41	0,44	0,44	0,50	0,52	0,60	0,64	0,66
Kosovo	:	:	:	:	:	:	:	:	1,00	1,00	1,00

Source: Eurostat (online data code: tour_cap_nat).

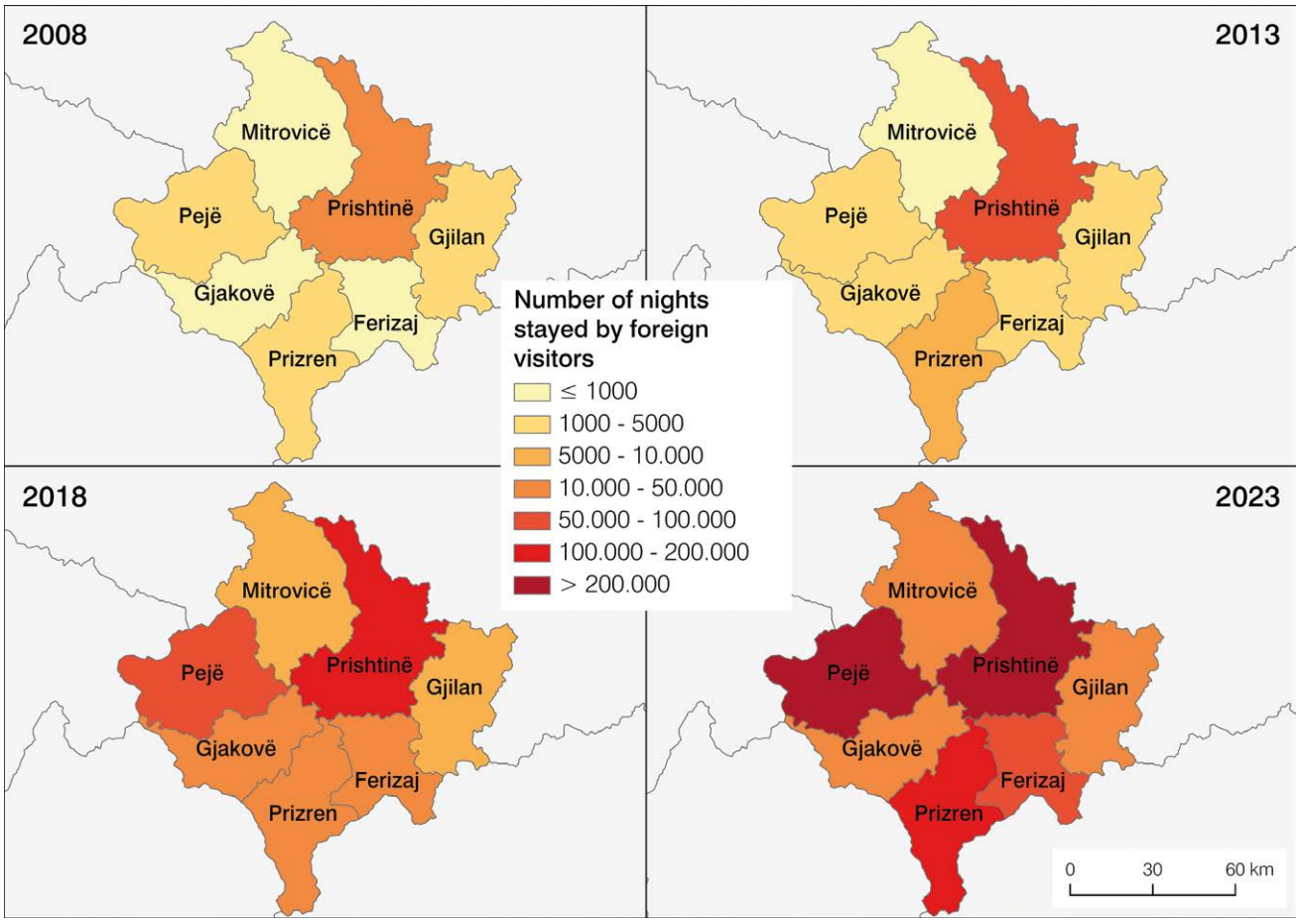

Fig. 5 Number of overnight stays of foreign visitors by region in Kosovo in 2008, 2013, 2018 and 2023.

5. Data analysis and discussion

This chapter provides an overview of the most important geopolitical events during the period from 2008 to 2023 in Kosovo and the number of foreign tourist arrivals for every year (Tab. 4). Each geopolitical event was marked as negative (−1), positive (+1) or neutral (0) so that at the end they could be summarized for each year. The method assumes that geopolitical stability functions as a key determinant of tourist behavior. The purpose of classifying geopolitical events qualitatively is to translate complex political developments into measurable indicators that can be analyzed in relation to tourism dynamics. Tourism demand, especially in politically sensitive regions such as Kosovo, is highly dependent on perceptions of safety, stability, and international recognition. Since statistical indicators of stability (like conflict index which takes into consideration four indicators – deadliness, danger to civilians, geographic diffusion, and the number of armed groups. or travel warnings) may not exist for every year, we have applied a qualitative event scoring system. It captures the *direction and intensity* of political conditions. This classification provides a standardized ordinal scale that enables correlation testing between *geopolitical context* and *tourist arrivals*. That way, we can get an overview of geopolitical climate for that year. For the purpose of establishing correlation Pearson Correlation Coefficient is used. Thus, we should be able to get interconnection between these events and, on the other hand, decrease/increase of tourist visits which can be the result of those geopolitical events (except in the years of COVID pandemic), if this interconnection exists.

The table evidently shows that the number of tourist arrivals has varied significantly from year to year. The average number of tourist arrivals in the last 15 years has been 135,099 tourists per year. Tourism responses are often lagged and nonlinear, shaped by perception, media framing, and cumulative change rather than single events. Kosovo declared independence in 2008, which is a major geopolitical milestone, but tourism did not increase in 2009, even stayed stagnant. This can be explained by uncertainty (travelers, especially international ones, need time to adjust to a new geopolitical reality), and violence and protests in 2008 (Mitrovica clashes) which neutralized the potential excitement of independence. That was an event which didn't show immediate impact.

In the period 2010–2011 there was a gradual decline as a result of the buildup border tensions, NATO clashes, and Serbia's pushback (2010: −1,936 tourists, 2011: −4,033 tourists). Even the most violent incidents occurred in mid to late 2011, the decline

Tab. 4 Most important geopolitical events and tourist visits in Kosovo between 2008 and 2023.

Year	Key geopolitical events	No. of tourists / Index (vs. previous year)	Rationale
2008	Feb 12th: Serbia condemned Kosovo's upcoming declaration of independence as a "terrorist act". Feb 17th: **Kosovo declared independence.** Jun 15th: Kosovo Constitution entered into force.	36,318	Independence caused regional instability and Serbian condemnation (−1)
2009	Jan 21st: Establishment of the Kosovo Security Force (KSF). Serbia protested. Apr 6th: EU Rule of Law Mission opened HQ in Pristina. Aug 25th: Clashes between Kosovo Serbs and Albanians in Mitrovica; protests in Pristina damaged 24 EULEX vehicles.	36,318* / 26.88	Unrest outweighed institutional progress (−1)
2010	Strategy for integration of northern Kosovo. Apr 19th: NATO transferred border control to Kosovo Police. May 30th: Belgrade-organized elections in Mitrovica led to conflict. Dec 12th: First general elections, followed by fraud allegations. Council of Europe report accused PM Thaçi of organized crime and organ trafficking. Oct 29th: KFOR announced troop reduction from 10,000 to 5,000.	34,382 / 25.44	Political and ethnic tensions prevalent (−1)
2011	Apr–Sep: **Severe border tensions** between Kosovo and Serbia. Jul 27th: NATO took control of border crossings. Jul 28th: Violence along Kosovo–Serbia border. Aug, Sept, Oct: Multiple violent clashes between Kosovo Serbs and NATO forces. Nov 28th: KFOR soldiers injured during protest clashes.	30,349 / 22.47	Severe unrest with NATO involvement (−1)
2012	Apr 8th: Bomb attack in Mitrovica condemned by UNMIK. Jul 17th: Russia convened meeting on Kosovo–Serbia violence. Sep 25th: Serbia showed good will for constructive negotiation process. Oct 19th: First prime minister-level talks between Kosovo and Serbia since 2008. Nov 27th: Steps toward normalization of relations.	48,790 / 36.11	Clear diplomatic progress despite isolated incidents (+1)
2013	Jan 17th: Continued EU-facilitated dialogue. "Interim agreements" on tariffs. March: Positive developments related to high-level political dialogue. Apr 19th: "First Agreement on Principles Governing Normalization of Relations." Jun: Progress in political dialogue. Ongoing challenges in northern Kosovo.	50,074 / 37.06	Breakthrough normalization year (+1)
2014	*No major geopolitical events recorded.*	61,313 / 45.38	Stable period – conducive to tourism (+1)
2015	Aug: Continued Belgrade–Pristina dialogue. Approval of constitutional changes enabling a Special War Crimes Court.	79,238 / 58.65	Continued normalization; legal progress (+1)
2016	Jun: UNMIK no longer administered the territory. Nov: Political tensions over Community of Serbian Municipalities formation.	163,987 / 121.38	Rising tensions overshadowed otherwise calm period (−1)
2017	Feb: Heightened tension between Belgrade and Prishtina over the course of past several months. May–Nov: Renewed nationalist rhetoric and loss of trust. Nov: US reaffirmed UNMIK had fulfilled its mandate.	162,234 / 120.08	Instability and rhetoric intensified (−1)
2018	Feb: Continued tensions over **Special Court repeal**. May: Positive developments over border demarcation. Nov 14th: Talks of territorial exchanges. Dec: Kosovo expanded Security Forces' jurisdiction.	192,761 / 142.68	Mixed year – modestly positive due to progress (+1/borderline)
2019	COVID-19 pandemic: *No major geopolitical developments recorded.*	177,358 / 131.28	Excluded from correlation due to pandemic (0)
2020	COVID-19 pandemic. Apr: Government collapse amid pandemic response.	85,215 / 63.07	Pandemic distortion – not representative (0)
2021	Oct: Tensions in northern Kosovo and along the Serbia–Kosovo border.	212,843 / 157.54	Northern Kosovo conflict returned (−1)
2022	Apr: Improving relations; attacks on police in northern Kosovo. Oct: Continued EU-facilitated dialogue. License plate dispute renewed tensions.	297,588 / 220.27	Balance between normalization and clashes (0/mixed)
2023	Feb: Agreement on proposal for normalization of relations. Apr, May: Tensions in northern Kosovo. Jun: NATO deployed 700 additional troops amid escalating tensions. Sep: Further escalation in Northern Kosovo.	357,717 / 264.78	Escalation dominated the year despite early progress (−1)

* Probable statistical error (Kosovo Agency of Statistics).
Source: Security Council Report (2024), Kosovo Agency of Statistics, Tourism and Hotels –Yearly indicators, 2008–2023.

started earlier, suggesting anticipation of instability or consistent negative news builds over time or tourism declines in expectation of further deterioration. It could be said that border disputes cause concern, but often don't deter tourism nationwide unless they escalate into open conflict.

Between 2012–2013 normalization talks and the first visible political cooperation started between Serbia and Kosovo which brought hope. The result was a sharp rise in tourism in 2012 (+18,441), continuing in 2013. Much of the positive diplomatic momentum began in the late 2011, but tourist numbers rebounded a year later. Time was necessary to build the confidence. No major conflict events occurring between 2014–2016, improved by EU dialogue, and easing UN involvement led to a surge in arrivals +11,239 (2014), +17,925 (2015), and a major leap of +82,996 in 2016. Even though political tension existed in 2016, it didn't reduce tourism. This shows that minor tensions don't always reverse positive momentum once perception stabilizes.

In the last years (2022–2023) despite escalating tensions, including NATO deployments, tourism increased significantly: +84,745 in 2022 and +60,129 in 2023. By now, Kosovo had developed a more stable tourism infrastructure, reputation, and repeat traveler base (diaspora, regionals). There's a "conflict fatigue" effect and unless a major war breaks out, tourists no longer overreact to low-level tensions.

If we calculate Pearson coefficient for all mentioned geopolitical events for the whole period from 2008 to 2023, and if we exclude COVID period (years 2019 and 2020), since it is not in the category of geopolitical events, the results are as follows: the Pearson correlation coefficient between the net geopolitical event score and tourist arrivals is approximately 0.039, with a p-value of 0.899. Correlation ($r = 0.039$) in this case indicates an extremely weak positive correlation, practically no linear relationship between geopolitical events (as scored here) and tourist arrivals. P-value (0.899) is not statistically significant, meaning there's no evidence of a meaningful linear relationship between net geopolitical event scores and tourist arrivals in this data set.

Besides, we can test the correlation separately for positive events (like diplomatic agreements and stability measures) versus tourist arrivals and negative events (conflicts, restrictions, weapon rattling) versus tourist arrivals. In case of positive events results show correlation (r) −0.450 and P-value 0.123. This shows a moderate negative correlation, but it's not statistically significant ($p > 0.05$).

In case of negative events correlation (r) is −0.239 and P-value 0.431. This is a weak negative correlation, and it's far from being statistically significant. Therefore, we can't confidently say that negative events affect tourist numbers either.

In addition we can conclude, that tourist arrivals rarely react instantaneously to geopolitical changes. Perceptions of safety, infrastructure readiness, and media narratives evolve gradually. Consequently, the impact of a protest, border clash, or a diplomatic breakthrough may influence travel decisions not in the same year but with a lag of 1 or more years.

Based on the provided data, the expected relationship between geopolitical events and tourism growth in Kosovo is complex but shows a general trend of resilience and eventual growth despite instability.

Tourism in Kosovo is one of the most important service industries and it was in a major crisis due to the Covid pandemic. This was the first big crisis in tourism sector after postwar period. Nevertheless, Kosovo's economic rebound moderated significantly in 2022 due to the fallout from Russia's war against Ukraine on energy prices and inflation, as well as a decline in investments and remittances (EU Commission, 2023). Kosovo's tourism trajectory shares both similarities and differences with other post-conflict destinations, such as Croatia and Bosnia and Herzegovina (assome non-European post-war countries). Development of tourism, can be based on preserved environment, cultural heritage and religious tourism. In addition, Kosovo could also become a potential destination of dark tourism or thanatourism. Considering that Kosovo is a country with war experience (1998–1999), some of the locations could develop the tourist offer of this type of tourism. The war in Kosovo left behind permanent consequences, namely the general destruction of settlements, ethnic cleansing, forced deportations, mass graves, etc. All of them remain recorded in people's memories, but equally in the landscape. Some of the potential locations that could be included in the offer, i.e., which could initiate development of dark tourism are war museums, memorial sites and those places that can be connected to heritage tourism at the same time.

Some of the monuments that already have symbolic and memorial meanings are the Adem Jashari Memorial complex in Prekaz (dedicated to the commander of the Kosovo Liberation Army and his family), the Heroinat monument in Pristina (dedicated to all women victims of sexual violence during the war) and the Rečak Memorial at the site of the 1999 massacre. All of them commemorate pivotal moments of violence, resistance, and loss (Security Council Report 2024; Kosovo Agency of Statistics 2023). Mitrovica, as a divided city, is still a symbol of ethnic tension and intolerance. In addition, it should be mentioned that there are museums and exhibitions dedicated to the Kosovo Liberation Army and the creation of the state itself.

Therefore, the inclusion of Kosovo in the development of dark tourism is very complex, because it is still partially contested politically and ethnically divided – which prevents visits to certain locations that could become initiators of dark tourism. However, if Kosovo persists with dark tourism development

it could strengthen the local economy in some local communities and regions and create new "post-conflict regions" based on branding. Croatia and Bosnia and Herzegovina (Vukovar, Sarajevo, Srebrenica) have already successfully done this., The implementation of dark tourism requires a tourism strategy that would be agreed upon by all actors, i.e., collaboration between the conflicting parties without further exploitation of war trauma. Whilst the commodification of trauma raises ethical concerns, dark tourism can both foster education, commemoration, and reconciliation when approached inclusively and sensitively (Light 2017).

Year after year, except for 2010, when a significant drop in the number of arrivals was recorded, as in the years related to the COVID pandemic, Kosovo has recorded an increase in the number of both foreign and domestic tourists. In 15 years, this number has increased by more than half a million, despite the fact that the number of accommodation capacities (both hotels and other accommodation units) has remained the same or is decreasing slightly. The Kosovo Tourism Strategy for 2024–2030 is also targeted, thereby demonstrating its seriousness and intention to make tourism one of the largest economic sectors in the country.

6. Conclusions

Analyzing geopolitics from a tourism perspective is still an under-researched topic geopolitical processes such as political insecurity, military coups, terrorism, war, nation building, territorial disputes, ethnic cleansing, global health crisis and so on, have a deep impact on tourism development.

Kosovo in the context of generalization effect that potential tourist considers the entire region unsafe, is still perceived as insecure destination. There are numerous reports on clashes between Kosovars and Serbs which are covered by the media and broadcasted in the world. Constant political and geopolitical instability generally and most seriously threatens tourism development. Qualitative classification of geopolitical events related to tourism in Kosovo into *positive* and *negative* categories provided results which showed how political (in)stability influences tourism development – in this case offering insights into the interdependence of political normalization and economic resilience.

In the context of laid research goals, the conclusion is following:

1) Ethnic tensions, organized crime and potential terrorist attacks are just some of the most common reasons related to geopolitical instability and Kosovo's unattractiveness as a tourist destination (at least at the beginning). Terrorism and violent attacks severely influence tourism, but in Kosovo their influence was short termed. For example, Mitrovica bombing in 2011 contributed to drop in tourism, but in 2012 situation was significantly better. According to the results, tourism was more sensitive to violent or terrorism-linked events (e.g., 2008–2011) than to border disputes or institutional issues. After 2012, even with recurring border clashes, growth continued, suggesting that tourists perceive the country as increasingly stable or that conflict zones are avoidable.
2) According to data, period between 2008 and 2011 was most critical for tourism in Kosovo since tourism numbers stagnated or declined, but this effect was not a longlasting one. In the following years, between 2012 and 2015, although tensions remained, tourism numbers improved significantly as the result of positive geopolitical events. After 2016 despite recurring tensions tourism consistently increased in most years. The sharp rise is possibly tied to improved infrastructure or new recognition of Kosovo as a destination. During 2017 a slight decline during renewed tensions appeared, but significant growth is recorded between 2021 and 2023, reaching 357,717 by 2023. This shows that the longer-term tourism trend is upward**.** In the short term**,** political instability and violence in Kosovo negatively affect tourism, while in the long term, political dialogue, normalization efforts, and gradual stability are strongly correlated with significant tourism growth.
3) Kosovo, compared to the other Western Balkan countries, has the lowest number of tourist beds, especially compared to Albania and Montenegro. Moreover, tourism is a significant contributor to the services sector in Montenegro and Albania. Tourism's direct contribution to the GDP in these countries is almost 9%, while its indirect contribution is estimated at over 20%, which is not the case in Kosovo. But this is to be expected, since these are Mediterranean countries which base their tourist offer on a different type of tourism. But, Kosovo still lags behind after Bosnia and Herzegovina and North Macedonia. The situation is better when analyzing the number of tourist beds per 1000 inhabitants, where Kosovo has a similar situation to Serbia and Bosnia and Herzegovina. Conclusion is that Kosovo's post-conflict tourism growth is on par with or slightly slower than other post-conflict nations, especially those with greater international recognition, stronger infrastructure, or EU connection.

Kosovo's geopolitical uniqueness creates a dual reality. On the one hand, conflict legacy, political issues and tensions restrict rapid tourism expansion. Though its distinct culture, strategic location, and gradual normalization position it for steady, resilient, and niche-driven tourism growth. Future research should explore tourists' perception data and some other models to better demonstrate lagged effects between geopolitical events and tourism behavior.

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