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Nonlinear and spatiotemporal dynamics of land finance and urban expansion in China: A GeoXAI-enhanced analysis

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ABSTRACT While land finance is a recognized institutional driver of urban expansion, the nonlinear and spatially heterogeneous dynamics of this fiscal mechanism remain underexplored. This study integrates geospatial explainable artificial intelligence (GeoXAI) with econometric models to decode the spatiotemporal evolution of the land finance – urban expansion nexus across 204 Chinese cities (2005–2020). By overcoming the limitations of traditional methods, we reveal that the impact of land finance on urban expansion is profoundly nonlinear, transitioning from a mitigating effect to a powerful reinforcing driver over time. Furthermore, this fiscal stimulus exhibits stark spatial disparities, with positive spatial interactions diffusing from coastal regions to inland second-tier cities. Ultimately, this research provides a novel methodological paradigm for spatial policy evaluation and extends the theoretical understanding of land urbanization for the emerging economies. These findings offer actionable insights for implementing zoned regulations and polycentric governance to curb inefficient urban sprawl driven by fiscal incentives.

KEY WORDS land finance – urban expansion – GeoXAI – nonlinear dynamics – spatiotemporal dynamics

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1. Introduction

Urban expansion is a global urban issue, especially for developing countries that are experiencing rapid urbanization. According to World Urbanization Prospects, the world's urban population is likely to increase by 2.5 billion people by 2050, with nearly 90% of this growth occurring in Asia and Africa (UN 2014). Urban expansion is reshaping the urban-rural structure of developing countries, and at the same time bringing unprecedented opportunities and challenges to developing countries. On the one hand, urban expansion can lead to more employment opportunities and improve economic incomes (Zhang 2016), while promoting social mobility based on this (Hatab et al. 2022); on the other hand, unorganized urban expansion is believed to lead to biodiversity degradation (McDonald et al. 2020), increased carbon emissions (Wu et al. 2022), higher costs of public services and health inequalities (Garden, Jalaludin 2009). As one of the fastest urbanizing countries in the world (Hu et al. 2024), the average built-up area of Chinese cities was 90.78 km² in 2005, and by 2020, the average built-up area of Chinese cities was 180.16 km², an increase of 98.46% (Ministry of Housing and Urban-Rural Development of China 2005, 2020). This rapid and widespread urban expansion is the result of a combination of factors.

Land finance is recognized as an important driver of urban expansion in China at the institutional level. Since the formal implementation of the tax-sharing fiscal reform in 1994 and the Ministry of Land and Resources of China explicitly promoted land market reform in 2002, land transfer fees have become an important source of revenue for local governments, and a more serious land finance dependence has developed in some regions (Fan, Qiu, Sun 2020; Yu, Zhou 2024). Recent studies have emphasized that land finance is both a driver of China's rapid urbanization and a cause of inefficiency in urban expansion, and that the Chinese government is moving away from an over-reliance on land finance through comprehensive reforms. That is, by exploring a path to address the fiscal needs of local governments while at the same time addressing the environmental and social costs of urban expansion (Gyourko et al. 2022, Zhang et al. 2023). Therefore, scholars have examined the relationship between land finance and urban expansion, as well as their regional heterogeneity, spatial spillovers, and mechanisms (Tong et al. 2023; Yu, Zhou 2024), and based on this, they have provided policy recommendations to help the Chinese government to get rid of the dependence on land finance and to realize the balance between urban expansion and sustainable development. However, existing studies are still insufficient in revealing the nonlinear relationship and spatiotemporal heterogeneity between land finance and urban expansion.

Although some recent studies have begun to focus on the nonlinear relationship between land finance and urban expansion (Chen et al. 2024, Tong et al. 2023,

Zhang et al. 2023), these studies usually rely on traditional econometric models (e.g., threshold models or quadratic term models), and thus may oversimplify the polynomial or discontinuous relationship between land finance and urban expansion. In addition, case studies from Chongqing, Wuxi and Foshan, reflect that there may be potential spatiotemporal heterogeneity between land finance and urban expansion (Liu et al. 2018a, Tian 2015). Although preliminary explorations have been conducted using multiscale geographically weighted regression with a spatial Durbin model (Yu, Zhou 2024; Zhang et al. 2023), since both are fundamentally a modeling approach based on linear assumptions, they may lead to model misspecification and performance degradation. At this point, there is an urgent need to introduce emerging geographic machine learning methods to cope with the above dilemma. It is noteworthy that a recent pioneering study has attempted to explore nonlinear and spatial non-stationary effects simultaneously using a geographically weighted-random forest with SHapley Additive exPlanation (SHAP) framework, providing novel insights (Zhang et al. 2025). However, this framework treats spatial features as separate features, which violates the theoretical properties of the Shapley value (Harris, Pymar, Rowat 2021). Additionally, the framework is constrained by the fact that the R software does not provide a module for analyzing interaction effects (Zhang et al. 2025), thus failing to analyze the interaction between land finance and spatial features.

In summary, this study seeks to address the research question: How does land finance influence urban expansion in China, and how do these effects vary across space and time under fiscal incentives? At the methodological level, we chose to introduce the GeoShapley method proposed by Li (2024), and used Bayesian hyperparameter optimization to obtain the optimal algorithm (XGBoost) and its hyperparameters, constructing a novel geospatial explainable artificial intelligence (GeoXAI) framework. Secondly, we combined the generalized additive model (Hastie, Tibshirani 1986) to capture the nonlinear relationship between land finance and urban expansion. Thirdly, we achieved the exploration of spatiotemporal heterogeneity by drawing spatial distribution maps of GeoShapley values of land finance. Finally, we applied the basic principles of the moderation effect to analyze the spatial interactions of land finance.

2. Theoretical foundations and prior research

2.1. Concepts and measurement of land finance and urban expansion

Land finance is not an internationally standardized term, but rather refers to a distinctive fiscal behavior pattern formed by local governments in China under the institutional context of the tax-sharing fiscal reform and public land ownership,

characterized by a heavy reliance on land conveyance and related financing instruments (Qiu 2025). In developed countries, property taxes typically serve as the land-related fiscal source supporting urban operations, whereas in China, the transfer of commercial and residential land use rights constitutes the core extrabudgetary revenue source for local governments to finance urban infrastructure construction (Wang et al. 2020). Against this backdrop, this study follows the mainstream approach and employs land transfer fees as a proxy variable for land finance.

When examining urban spatial evolution, it is essential to distinguish among the concepts of urbanization, urban sprawl, and urban expansion. Urbanization, as a macro-level economic and sociological concept, encompasses a process involving both urban population growth and urban land transformation. In contrast, urban expansion specifically denotes the continuous expansion of urban built-up areas, which can intuitively reflect land use changes during the urbanization process (Li et al. 2025, Mahtta et al. 2022). When the pace of such spatial expansion significantly exceeds the rate of population migration from rural to urban areas, the originally neutral concept of urban expansion evolves into a pejorative notion, namely urban sprawl. Given that land finance directly affects urban construction land, this study adopts changes in built-up area as a proxy variable for urban expansion.

2.2. Urban expansion under fiscal incentives

From a global perspective, the development of human settlements is profoundly shaped by fiscal decentralization and local policies. Within fiscal decentralization systems, the autonomy granted to local governments incentivizes them to maximize fiscal revenue through the utilization of land development permits and land use regulations. Empirical evidence from Europe supports this argument and further suggests that in decentralized countries, fiscal incentives at the local level may provide strong incentives to permit residential development at the outskirts of existing developments (Ehrlich, Hilber, Schöni 2018). Consequently, the outward expansion of urban space transforms from a purely demographic-geographic phenomenon into a fiscally driven economic behavior (Oates 1999).

This phenomenon is particularly pronounced in emerging economies, where local governments face immense pressure to provide public services and infrastructure during rapid urbanization. The resulting escalation of municipal expenditures inevitably renders local governments dependent on land finance. Specifically, land transfer fees and related taxes generate substantial extrabudgetary revenues for municipal budgets, the majority of which are subsequently invested in infrastructure construction on undeveloped land, thereby

progressively pulling urban boundaries outward. When land markets remain active, this fiscal feedback loop binds land finance and urban expansion together. However, when land markets begin to contract, the expansionary driving effect of land urbanization weakens accordingly, gradually yielding to population urbanization processes.

From a comparative perspective, urban spatial expansion in developed countries is primarily driven by household residential preferences and property tax dynamics (Chettry 2023; Tikoudis, Dimitropoulos, Oueslati 2018), whereas emerging economies rely more heavily on land finance-driven land urbanization. China represents a paradigmatic case. Against China's distinctive institutional environment and historical backdrop, the local fiscal gap created by the tax-sharing reform has intensified local governments' dependence on land finance. Due to regional variations in land prices, industrial structure, and transportation infrastructure, this local government led urban spatial expansion is bound to exhibit spatial heterogeneity across geographical space. Thoroughly exploring these spatial disparities is of considerable theoretical importance. However, traditional econometric methods possess inherent limitations in capturing localized spatial nonlinearity and heterogeneity, rendering the introduction of GeoXAI imperative.

2.3. GeoXAI and its applications in urban geography

To address the black box problem of machine learning algorithms, explainable artificial intelligence (XAI) has risen to prominence in recent years (Chamola et al. 2023, Dwivedi et al. 2023). Among various frameworks, the SHAP framework-based game theory has gradually become mainstream owing to its rigorous mathematical foundations and intuitive interpretability (Lundberg, Lee 2017). However, this framework assumes feature independence, thereby overlooking the spatial dependence and spatial heterogeneity of locational information during the modeling process (Li 2024; Xing, Sieber 2023). Against this backdrop, improved frameworks incorporating geographical interaction mechanisms, with GeoShapley serving as a representative example, have emerged. Its capacity to not only compute the global contribution of non-spatial features but also decompose such contributions into spatial interaction effects and intrinsic individual effects (Li 2024). Currently, the GeoShapley framework is offering a novel perspective of urban geography. On the one hand, scholars have employed this framework to disentangle the impacts of built environment on elderly walking ability and child friendly perception (Su et al. 2025a, 2025b), thereby expanding the evaluative boundaries of built environment elements such as streetscape and green space coverage. On the other hand, scholars have leveraged this framework to predict

road accident risks (Srivastava, Gohil, Ray 2025), consequently improving urban planning and traffic dispatching. More fundamentally, the contribution of GeoXAI to urban geography extends beyond enhancing the predictive accuracy of models, it also facilitates the identification of whether a particular driving factor acts as an enabler or a barrier at different geographical locations. Therefore, the introduction of GeoXAI into the investigation of the relationship between land finance and urban expansion is imperative.

3. Methodology

3.1. Variables

The land finance revenue of local governments in China consists of land transfer fees and land-related taxes. Considering that land transfer fees are the most important source of local government revenue and that land tax-related data are difficult to collect, we draw on the idea of Sun and Zhou (2013) to use land transfer fees as a proxy variable for land finance and logarithmically treat them in the modeling process.

Urban expansion in China mainly manifests as the excessive expansion of urban space and urban population (Lyu, Huang, Sun 2025). Considering that this study mainly explores the driving role of land finance in the urbanization process. Therefore, we set 2002 as the base period and measure urban expansion by the ratio of the built-up area of each prefecture-level city in the study year to the built-up area in the base period, as shown below:

$$URBS = \left(\frac{S_t}{S_0} - 1\right) \times 100\% \tag{1}$$

Based on previous literature (Osman, Divigalpitiya, Arima 2016; Sudhira, Ramachandra, Jagadish 2004), we will select control variables from three aspects: economics, population, and geography. In the economic dimension, this study selects GDP per capita and industrial structure as control variables. GDP per capita serves as an intuitive indicator of a region's overall level of economic development, while industrial structure directly determines the spatial pattern and intensification degree of land use. In the population dimension, population size and urbanization level are incorporated into the model. The sustained growth of the urban permanent population generates rigid demand for housing, and the large-scale migration of the rural population to cities constitutes the fundamental driving force behind the outward expansion of urban built-up areas. In the geographical dimension, location, geographic region, and topographic relief are introduced as control variables. Location and geographic region are

constructed as dummy variables, typically reflecting structural differences in fiscal resources and development trajectories across different regions of China, whereas the topographic relief derived from remote sensing image processing directly captures the natural constraints that geomorphological features impose on urban construction. The multisource panel dataset thus constructed provides a solid foundation for revealing the complex relationship between land finance and urban expansion.

3.2. Data source

After removing missing values from the variables, a sample of 204 prefecture-level cities in China was retained, with the study years including 2005, 2010, 2015, and 2020. In terms of data sources, land finance was obtained from the *China Land and Resources Statistical Yearbook*, urban expansion from the *China Urban Construction Statistical Yearbook*, and the remaining control variables from the *China City Statistical Yearbook*, the GTOPO30, and statistical yearbooks of various provinces and cities. The descriptive statistics of each variable are shown in Table 1.

Table 1 – Descriptive statistics

Variables	Symbol	N (%)	Mean ± Std	Definition
Land finance	Lnx		3.821 ± 1.557	Natural logarithm of (total land transfer revenue + 1) in the year
Urban expansion	Y		2.136 ± 1.244	Growth rate of built-up area compared to the baseline period
Per Capita GDP	E1		10.395 ± 0.816	Natural logarithm of per capita GDP
Industrial Structure	E2		41.131 ± 10.246	Share of tertiary industry value added in GDP (%)
Urbanization	P1		0.522 ± 0.176	Urbanization rate
Population Size	P2		5.987 ± 0.697	Natural logarithm of resident population
Geographic Region	G1			Defined by National Bureau of Statistics of China
Eastern		328 (40.20%)		
Central		268 (32.84%)		
Western		212 (25.98%)		
Northeastern		8 (0.98%)		
Location	G2			Coastal or Inland
Inland		472 (57.84%)		
Coastal		344 (42.16%)		
Topographic Relief	G3		0.671 ± 0.736	Terrain relief derived from remote sensing image processing

3.3. Research methods

To comprehensively examine the evolutionary characteristics of land finance and urban expansion and their complex nexus, this study develops an integrated analytical framework. First, kernel density estimation is employed to characterize the distribution patterns and polarization phenomena of land finance and urban expansion, and further to analyze their dynamic evolution. Second, a two-way fixed effects model is constructed to conduct a global test of the basic linear relationship between land finance and urban expansion, thereby establishing links with previous quantitative research. Third, considering that traditional econometric models struggle to capture the intricate nonlinear relationships and spatial heterogeneity between land finance and urban expansion, this study adopts XGBoost as the base learner and utilizes GeoShapley along with the generalized additive model to present the estimation results in a more intuitive manner. Finally, drawing on the principle of moderation effects, a temporal analysis is performed on the spatial interaction terms derived from GeoShapley. The detailed flowchart is illustrated in Figure 1.

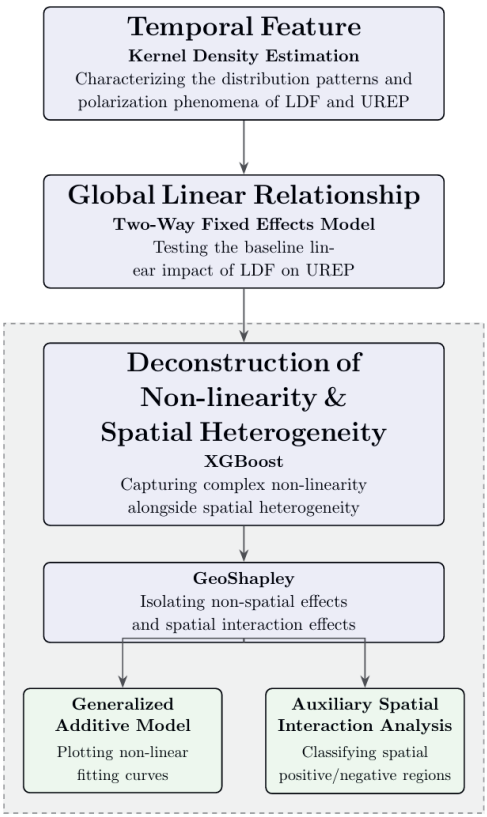


Fig. 1 – Comprehensive methodology framework

3.3.1. Kernel density function

The distribution location, distribution shape, extension characteristics, and polarization phenomena of land finance and urban expansion are characterized by the Gaussian kernel function to measure their dynamic evolution characteristics. The formula is as follows:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{D_i - \overline{D}}{h}\right) \tag{2}$$

In this formula, n is the number of prefecture-level cities; h is the smoothing bandwidth; $\overline{D}$ is the mean of the core variables; and $K(\cdot)$ denotes the kernel density function.

3.3.2. Two-way fixed effects

Test the linear effect of land finance on urban expansion by constructing a two-way fixed effects model:

$$Y_{i,t} = \delta_0 + \delta_1 Lnx_{i,t} + \delta_2 Z_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (3)$$

In equation (3), δ_0 is the intercept term, δ_1 and δ_2 represent the estimated coefficients of land finance and control variables, respectively, and μ_i, λ_t, and $\varepsilon_{i,t}$ represent the city (individual) fixed effect, year (time) fixed effect, and random disturbance term, respectively.

3.3.3. XGBoost

XGBoost is an efficient and scalable ensemble learning algorithm based on the gradient boosting framework, which can be applied to both regression and classification tasks. Its core idea lies in iteratively training decision trees to gradually optimize the model, with the objective of minimizing the model's loss function in each iteration. Furthermore, compared with the traditional GBDT, XGBoost further enhances the model's generalization ability and robustness by introducing a regularization mechanism (Chen, Guestrin 2016). The calculation formula of its objective function is:

$$\varphi(\theta) = \sum_{i=1}^{n} l(y_i, \hat{y}^{(t)}) + \sum_{k=1}^{t} \Omega(f_k) \quad (4)$$

Among them, $\varphi(\theta)$ is the objective function, which consists of two parts: the loss function and the regularization term. $l(y_i, \hat{y}^{(t)})$ is the loss function, which is used to measure the prediction error of the model. $\Omega(f_k)$ is the regularization term, which is used to control overfitting.

3.3.4. GeoShapley

Generally, traditional regression analysis and the econometric methods extended from it mainly focus on identifying linear relationships, while the emerging machine learning models in recent years have significant advantages in recognizing complex relationships among variables (Cao, Tao 2023). Meanwhile, considering that the core variables in this study exhibit significant spatial agglomeration effects, if spatial heterogeneity is not considered during modeling and machine

learning algorithms are directly applied to construct a global model, it will be impossible to accurately describe the local relationships between spatial variables, leading to weak model interpretability (Yang et al. 2023). Therefore, we chose to apply GeoShapley, the geospatial extension of the SHAP framework – the most popular explainable machine learning framework – to strengthen the analysis of spatial heterogeneity and improve the interpretability of modeling results (Foroutan, Hu, Li 2025; Li 2024). Its final output formula consists of four parts (Li 2024):

$$\hat{y} = \phi_0 + \phi_{GEO} + \sum_{j=1}^{p} \phi_j + \sum_{j=1}^{p} \phi(GEO, j) \tag{5}$$

Among these, ϕ_0 is the global intercept calculated based on the average predicted value of the given data, ϕ_j represents the location-independent effect provided for each non-location variable, ϕ_{GEO} is the inherent location effect in the model, and $\phi(GEO, j)$ represents the interaction effect between location and a specific variable. When there is no location information in the model, ϕ_{GEO} and $\phi(GEO, j)$ will be 0, and the equation will revert to the classic Shapley value calculation equation.

3.3.5. Generalized additive model

To better explain the nonlinear relationship between land finance and urban expansion, we combined machine learning algorithms with generalized additive model to plot the fitted curve (Hastie, Tibshirani 1986), as shown in the following formula:

$$g(E(y)) = \beta_0 + s(v) \tag{6}$$

Among them, $g(E(y))$ represents the expected response $E(y)$ of the dependent variable y after being acted upon by the link function g, where β_0 is the intercept term, and $s(v)$ is a smooth function of the GeoShapley values of the independent variables.

3.3.6. Methods for auxiliary analysis of spatial interactions

Since the spatial interactions in GeoShapley essentially represent interaction terms between independent variables and spatial features, their numerical values cannot be directly analyzed. Therefore, we chose to draw on the fundamental principles of the moderation effect (Cohen et al. 2013; James, Brett 1984) for analysis. Specifically, when the sign of land finance is the same as that of its spatial interaction term, it is regarded as a spatial reinforcing effect; conversely, it is a spatial weakening effect. According to the sign of land finance, this can be further subdivided into four categories: positive spatial reinforcement, negative

spatial reinforcement, positive spatial weakening, negative spatial weakening. In the results section, we will also conduct an analysis following this logic.

Except for the two-way fixed effects models constructed using Stata/MP 17.0 and the spatial feature maps drawn using ArcGIS 10.8, all other data processing, modeling, and visualization were implemented via Python 3.11.7. The research framework diagram of this study is shown in Figure 1.

4. Results

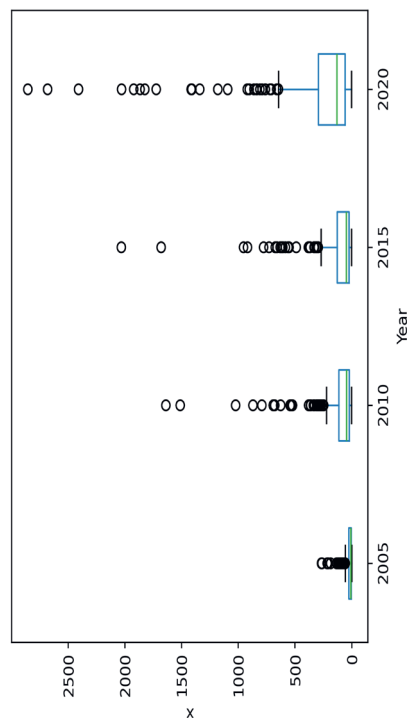
4.1. Temporal characterization of land finance and urban expansion

Figures 2 and 3 illustrate the temporal changes in land finance and urban expansion of China's prefecture-level cities from 2005 to 2020[1]. The figures show that both land finance and urban expansion exhibited a sustained growth trend during the study period. The mean value of land finance increased from 24.582 to 298.810, representing a 1116% growth, while the mean value of urban expansion rose from 1.346 to 2.950, a 119% increase. Additionally, the medians of land finance and urban expansion continuously increased, but the box sizes of their boxplots also expanded. The kernel density curves shifted rightward overall, yet the peak values of the main peaks significantly decreased, and the amplitude widths substantially widened. In summary, the continuous growth of land finance and urban expansion during the study period was accompanied by an expanding regional disparity.

4.2. Average direct effect of land finance on urban expansion

Before constructing the regression model, we analyzed whether there was a correlation between the independent variables and the dependent variable, and the results showed that there was a positive correlation between land finance and urban expansion ($r = 0.355$, $P < 0.001$). Figure 4 shows the univariate regression equation of the land finance and urban expansion and its fitted line, which also verifies the positive correlation between the land finance and urban expansion. Secondly, we also tested for multicollinearity between the variables. The results of the test showed that the maximum value of VIF was 3.35 (< 10) and the mean value was 2.45 (< 5), indicating that the possibility of multicollinearity among the selected variables is not significant. Meanwhile, the result of Hausman test ($\chi^2 = 83.04$, $P < 0.001$) rejected the original hypothesis of accepting the random

[1] For a more intuitive presentation, we did not logarithmically process the land finance in the process of plotting the temporal and feature maps.



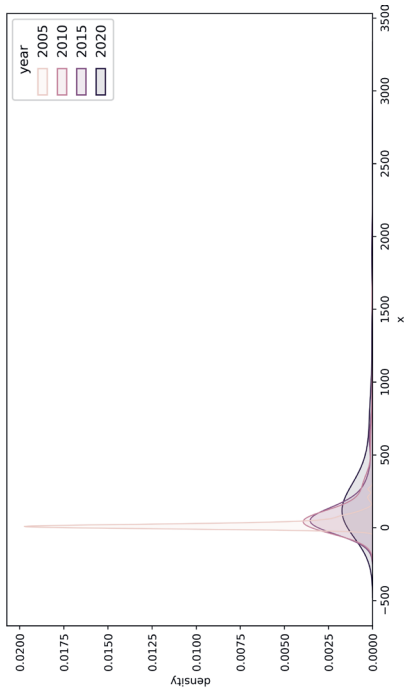


Fig. 2 – Temporal changes of land finance

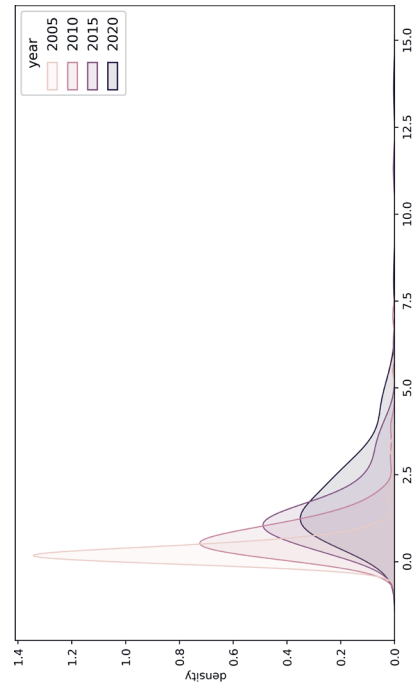


Fig. 3 – Temporal changes of urban expansion

Table 2 – Estimation results of the two-way fixed effects model

	Model 1	Model 2	Model 3	Model 4
Independent variable	0.458***	0.181***	0.148***	0.091*
	(0.022)	(0.031)	(0.032)	(0.043)
Covariates	×	√	√	√
City effect	×	×	√	√
Year effect	×	×	×	√
Constant	0.387***	0.354	-0.461	0.949**
	(0.110)	(0.383)	(0.244)	(0.323)
N	816	816	816	816
R^2	0.126	0.199	0.157	0.241

Note: * p < 0.05, ** p < 0.01, *** p < 0.001.

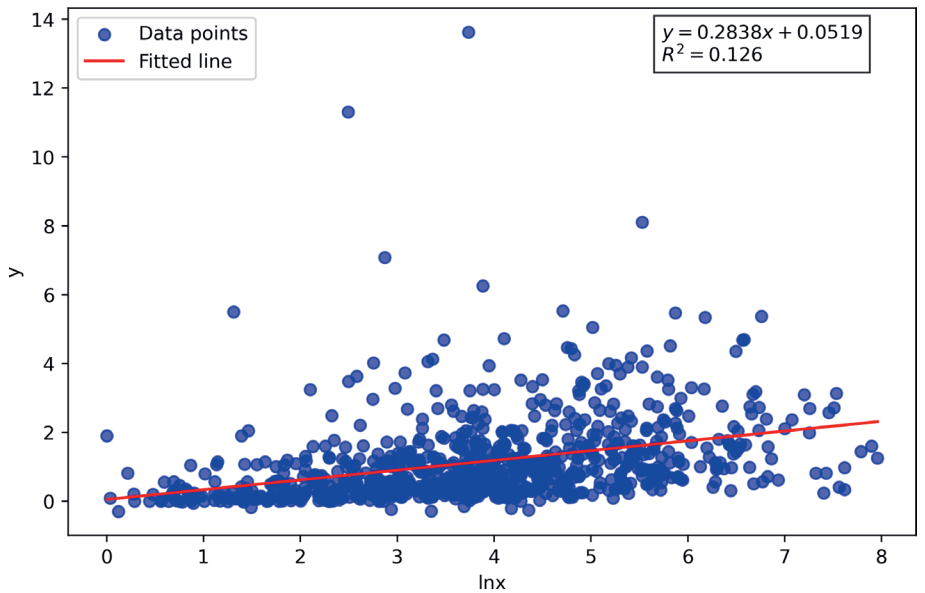


Fig. 4 – Fitted plot of land finance and urban expansion

effect model and initially identified the use of fixed effect model. Furthermore, we found that the estimated coefficients of the time term were significant and the R^2 of the model was improved after we added the time fixed effect, so we chose to use the two-way fixed effects model as the benchmark model.

The regression results are shown in Table 2. Among them, Model 1 is the OLS model, and Model 2, Model 3 and Model 4 are based on which control variables, individual fixed effects and time fixed effects are added, respectively. In the following, Model 4 will be analyzed as the benchmark model. Since the independent

variables have been taken as logarithms and the units of the dependent variables are percentages, it can be concluded from Model 4 that for every 1% increase in land finance, there will be a 0.091% increase in urban expansion ($B = 0.091$, $P < 0.05$). In addition, land finance significantly and positively affects urban expansion regardless of the inclusion of fixed effects with control variables, which validates the robustness of the benchmark results.

4.3. Nonlinear characterization of the relationship between land finance and urban expansion

Due to the performance of machine learning regressors being largely influenced by hyperparameters (Probst, Boulesteix, Bischl 2019), we adopted BayesSearchCV from scikit-optimize to tune the hyperparameters of XGBoost, RandomForest, AdaBoost, and LightGBM. BayesSearchCV is a Bayesian optimization method designed for efficiently searching global optimization problems (Mesquita,

Table 3 – Models and their hyperparameter tuning

Algorithm	Hyperparameter Name	Hyperparameter Type	Hyperparameter Range
XGBoost	learning_rate	Real	0.01–0.3 (prior = 'log-uniform')
	max_depth	Integer	3–10
	n_estimators	Integer	100–1,000
RandomForest	n_estimators	Integer	100–500
	max_depth	Integer	3–20
	min_samples_split	Integer	2–10
AdaBoost	n_estimators	Integer	50–200
	learning_rate	Real	0.01–1.0 (prior = 'log-uniform')
	loss	Categorical	['linear', 'square', 'exponential']
LightGBM	learning_rate	Real	0.01–0.3 (prior = 'log-uniform')
	max_depth	Integer	3–15
	n_estimators	Integer	100–1,000
	subsample	Real	0.6–1.0
	colsample_bytree	Real	0.6–1.0

Table 4 – Model evaluation results

	MAE	RMSE	R^2
XGBoost	0.447	0.658	0.766
RandomForest	0.592	0.853	0.608
AdaBoost	0.737	0.976	0.487
LightGBM	0.583	0.805	0.651

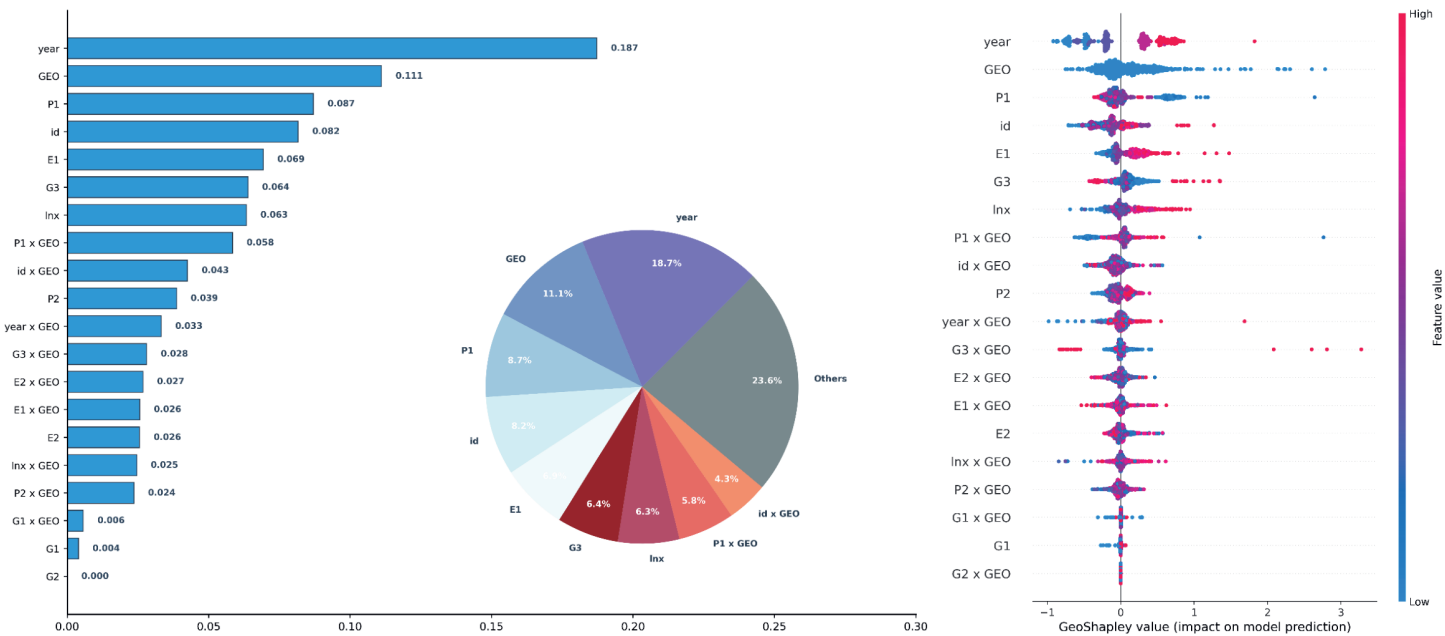


Fig. 5 – Variable importance and contribution percentage for the model

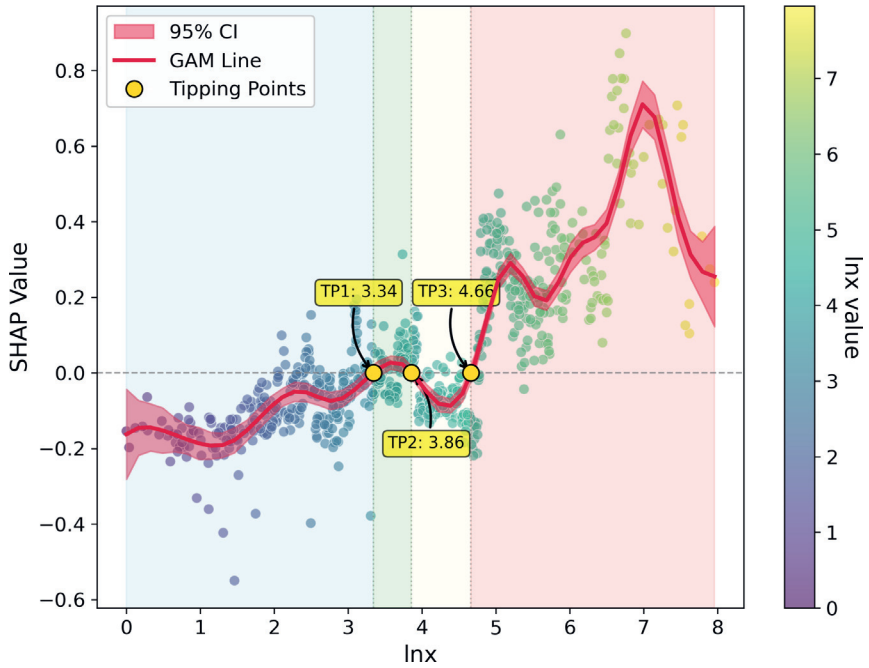


Fig. 6 – Nonlinear relationship between land finance and urban expansion

Marques 2024). During the hyperparameter optimization, all algorithms employed 5-fold cross-validation to ensure the robustness of model performance evaluation, with 30 iterations set and R^2 as the evaluation metric. The specific hyperparameter optimization items and ranges are shown in Table 3.

By comparing the evaluation indicators of each algorithm in Table 4, it can be found that XGBoost outperformed the other three models in R^2, *RMSE*, and *MAE* metrics (*MAE* = 0.447, *RMSE* = 0.658, R^2 = 0.766). Thus, based on the optimal hyperparameters, we constructed a GeoXAI framework to analyze the nonlinearity and spatiotemporal heterogeneity of the relationship between land finance and urban expansion in China's prefecture-level cities.

By taking the absolute values of GeoShapley values for each variable of every sample, averaging them, and sorting them sequentially, a variable importance summary plot was obtained (Figure 5)[2]. As shown in Figure 5, temporal effects, spatial effects, and individual effects are the three most important influencing

[2] Since the schematic diagram only supports displaying the top 20 variables and their spatial interaction effects, and the impacts of the last few variables and their spatial interaction effects on the model are almost negligible, we only present the top 20 variables and their spatial interaction effects here.

factors. land finance ranks 7th in the importance ranking of all variables and their spatial interaction effects, with a feature contribution of 6.3%, which is higher than that of population size and industrial structure – factors traditionally considered to have significant impacts (Li, Li 2019; Liu et al. 2018b). Meanwhile, Figure 6 indicates that when land finance is at a lower value, its impact on urban expansion is predominantly negative, whereas when land finance is at a higher value, the impact is predominantly positive. In other words, the relationship between land finance and urban expansion is not a simple linear one.

To further explore the potential nonlinear relationship, we plotted a partial dependence plot of land finance's GeoShapley values and combined it with a generalized additive model to draw a fitting line for better visualization of the nonlinear effect. Figure 6 shows that the fitting line between land finance and urban expansion has three tipping points, corresponding to the original data values of $27.22(e^{3.34}-1)$, $46.47(e^{3.86}-1)$, and $104.64(e^{4.66}-1)$. This indicates that when land finance is less than 27.22, its overall impact on urban expansion is negative; when its value is between 27.22 and 104.64, it exhibits an inverted U-shape followed by a U-shape relationship; and when the value exceeds 104.64, the impact on urban expansion is overall positive. In essence, the relationship between land finance and urban expansion is characterized by complex nonlinearity.

4.4. Spatiotemporal heterogeneity of the relationship between land finance and urban expansion

To more intuitively characterize the spatiotemporal heterogeneity of the impact of land finance on urban expansion, the GeoShapley values of land finance for each study year were visualized using the equal interval classification method (Figure 7). Based on Figure 7, it was found that during the study period, the impact of land finance on urban expansion gradually shifted from negative to positive, with continuously enhanced effects. High-positive-value regions were mainly concentrated in second-tier cities and showed a trend of diffusion from the coast to the inland. Specifically: In 2005, except for some cities in the Yangtze River Delta, some cities in the Bohai Rim, and a few inland cities, land finance in the remaining regions had a negative impact on local urban expansion. Only 12.75% of prefecture-level cities showed that land finance had a positive impact on urban expansion. In 2010, 45.59% of prefecture-level cities had land finance exerting a positive impact on urban expansion, presenting a trend of diffusion from the coast to the inland. The positive impacts of land finance on urban expansion were particularly prominent in Ningbo, Suzhou, and Dalian. In 2015, 48.53% of prefecture-level cities had land finance positively affecting urban expansion. The number of positive value regions slightly increased, but the polarization

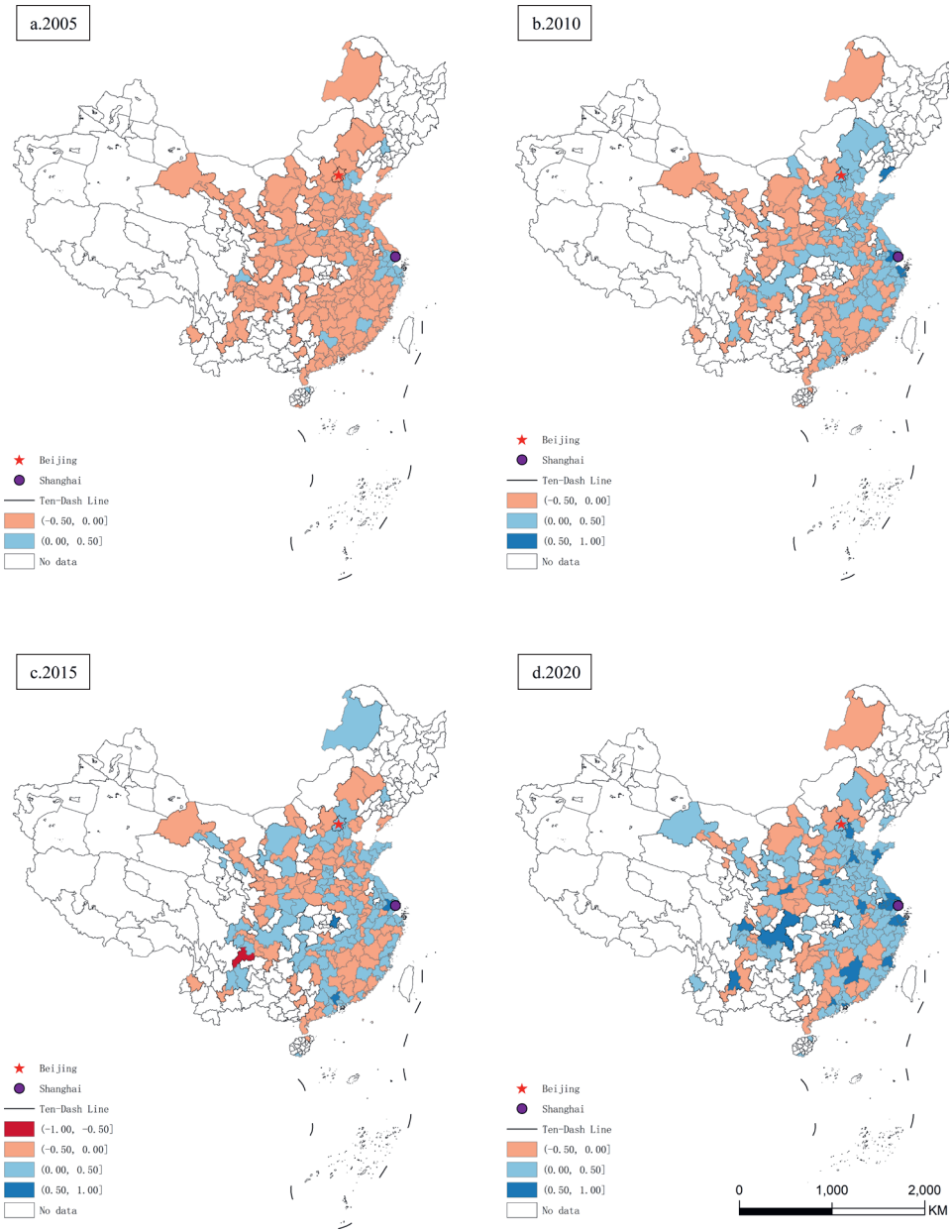


Fig. 7 – Spatiotemporal heterogeneity of land finance's Impact on urban expansion

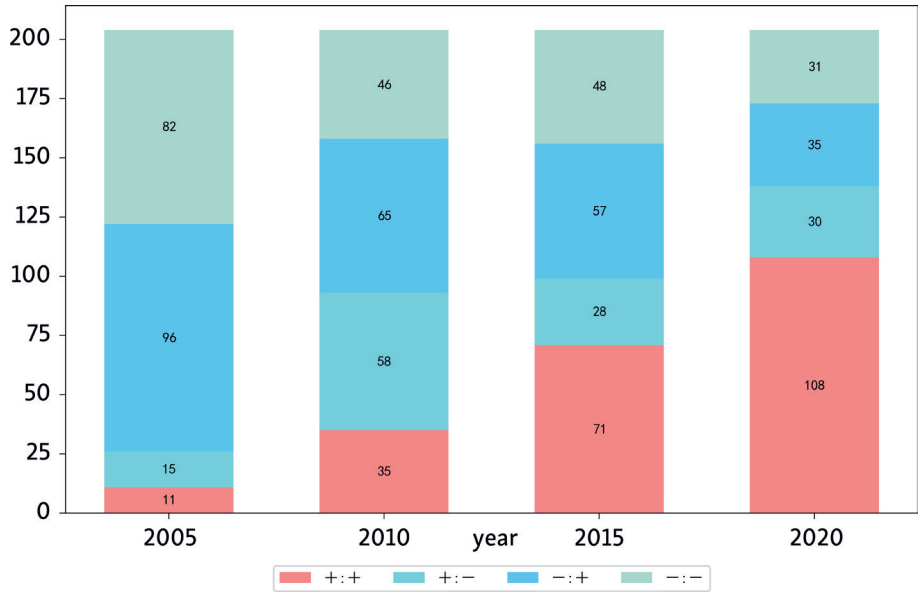


Fig. 8 – Proportion of different types of spatial Interaction effects

trend intensified. For example, land finance in Zhaotong, Yunnan significantly weakened local urban expansion. In 2020, 67.65% of prefecture-level cities saw land finance exerting positive impacts on urban expansion. High-positive-value regions were concentrated in second-tier cities such as Foshan, Jinan, Xi'an, and Wuhan, reflecting that land finance is an important factor for urban expansion in late-developing cities.

On this basis, combined with the basic principles of moderation effects (Cohen et al. 2013; James, Brett 1984), the interaction terms between land finance and the GeoShapley values of spatial characteristics were analyzed, as shown in Figure 8. It can be seen from Figure 8 that in 2005, spatial interactions mainly alleviated the negative inhibition of land finance on urban expansion (47.06%), while by 2020, spatial interactions mainly strengthened the positive effects (52.94%). In other words, the main role of spatial interactions shifted from alleviating negative impacts to strengthening positive impacts. Meanwhile, the proportion of positive spatial interaction terms across all cities increased from 52.45% in 2005 to 70.10% in 2020, indicating that spatially positive correlation areas expanded continuously.

5. Discussion

5.1. The effectiveness of GeoXAI and its integrated application with traditional econometric models

This study integrates XGBoost with GeoShapley, representing a novel GeoXAI framework. Applying this framework to analyze the relationship between land finance and urban expansion in China's prefecture-level cities is both effective and necessary. On one hand, the model evaluation indicators of this study (*MAE* = 0.447, *RMSE* = 0.658, R^2 = 0.766) significantly outperform the traditional spatial panel regression model (Tong et al. 2023), and are basically on par with other studies using this method (Foroutan, Hu, Li 2025). This indicates that the model has strong explanatory power in analyzing the relationship between land finance and urban expansion in China's prefecture-level cities. On the other hand, as previously mentioned, the spatial econometric models commonly used in previous studies are fundamentally modeling methods based on linear assumptions, which are not applicable when exploring non-linear relationships. Although existing studies have attempted to solve this dilemma by introducing machine learning, they still only treat location features as separate features and do not consider the impact of spatial interaction effects in the modeling process. Therefore, this study chooses to introduce a novel GeoXAI framework, which effectively solves the above problems and realizes the effective estimation of non-linear effects and spatiotemporal heterogeneity.

In addition, we further draw on the idea of Qiu et al. (2025) to plot the fitted curve of GeoShapley value of the land finance through generalized additive model, which not only realizes the visual presentation of the nonlinear effect, but also identifies the tipping points of the nonlinear relationship with the help of the semiparametric model, maximizing the potential of GeoXAI in identifying nonlinear relationships. In addition, considering that spatial interaction effects need to be analyzed with direct effects, this study introduces the basic principle of moderation effects and explores the role of spatial features in the baseline relationship. In summary, this study effectively estimates the nonlinearity and spatiotemporal heterogeneity of the relationship between land finance and urban expansion in China's prefecture-level cities by integrating the GeoXAI with traditional econometric models.

5.2. Theoretical contributions

In response to the ongoing debate in the existing literature regarding the relationship between land finance and urban expansion, this study validates the driving

effect of land finance on urban expansion over an extended period using a large sample panel dataset. More importantly, it further uncovers the nonlinearity and spatial dynamics between the two, which helps clarify the underlying logic of how land finance translates into urban expansion. land finance is not a conventional on-budget revenue; rather, it is a financing model centered on land transfer and land mortgage. As in other emerging economies, most of its value-added gains are channeled into public infrastructure investment (Peterson 2009). Driven by fiscal incentives, local governments, which serve as the core suppliers in the primary land market, attract capital inflows by supplying industrial land at low prices while obtaining substantial extra-budgetary revenues by leasing commercial and residential land at high prices. This financing model directly results in a situation where, in practice, urban spatial expansion in China typically precedes population agglomeration. At the same time, under fiscal incentives, the impact of land finance on urban expansion is not static or linear; it exhibits dynamic temporal nonlinearity and spatial heterogeneity that are subject to market cycles and regional economic conditions. These findings extend the theoretical boundaries of land finance as a form of spatial intervention by local governments.

Furthermore, this study provides an important reference for land capitalization practices in rapidly urbanizing countries. The uniqueness of the Chinese model lies in the coupling of public land ownership and fiscal decentralization, which enables local governments to capture land value increments for decades to come in the form of one-time land conveyance fees, thereby providing adequate funding for infrastructure construction during rapid urbanization. Although China's institutional context is distinctive, the inherent logic of urban expansion under fiscal incentives holds significant theoretical insights for rapidly urbanizing countries. In such rapidly urbanizing regions as India and Latin America, local governments similarly face enormous infrastructure investment gaps (Jain 2023, Smolka 2013). This study offers a land capitalization approach under fiscal incentives, which not only helps advance the capitalization of land in a public ownership economy but also helps bridge local fiscal gaps and promote urban infrastructure investment.

5.3. The interpretation of the results

During the research period, both land finance and urban expansion exhibited steady growth, accompanied by widening regional disparities. The root cause lies in the well-documented interurban economic inequality in China (Hou, Gao 2025). Within the centralized tax system, local governments face uniform fiscal pressure, leading them to rely on land finance as the most effective revenue tool (Tong et al. 2022). This transforms economic inequality into land finance inequality.

Subsequently, unequal land finance provides varying degrees of impetus to cities' urban expansion, further reinforcing urban expansion inequality caused by economic inequality.

Using the two-way fixed effects model, this study finds that, on average, a 1% increase in land finance leads to a 0.091% rise in urban expansion, which is like the results of Tong et al. (2022) and again confirms the positive direct effect of land finance on urban expansion. Moreover, based on GeoXAI, this study finds that land finance's contribution to the predictive model ranks seventh among all variables, accounting for 6.3%, offering new evidence of land finance's relative importance in explaining urban expansion. Additionally, by fitting GeoShapley value with generalized additive model, this study identifies the tipping points in the non-linear relationship between land finance and urban expansion. This extends the previous "threshold interpretation" (Li et al. 2021, Zhang et al. 2023) and once again confirms the complex non-linear relationship between land finance and urban expansion.

Regarding spatiotemporal heterogeneity, this study finds that land finance's impact on urban expansion has evolved from negative to positive with an increasing effect during the research period. High-value areas are concentrated in second-tier cities and are gradually spreading from the coastal to the inland. This reflects that China's urbanization has reached a turning point (Bai, Shi 2025). Studies show that between 2010 and 2020, the growth of urban population and housing in first-tier cities gradually saturated, while second-tier cities experienced rapid growth (Shi et al. 2025). That is, the new round of land-based urbanization may be led by late-developing cities. Although coastal urban agglomerations were larger in scale at the baseline and maintained relatively high annual growth rates compared to inland ones (Hu et al. 2024), with the advancement of China's regional coordinated development policy, the traditional urbanization pattern is changing at an unprecedented speed.

Moreover, the results of spatial interaction analysis show that spatially positive correlation areas expanded continuously, indirectly proving the initial effectiveness of the regional coordinated development policy. From a temporal perspective, the role of spatial interaction has gradually shifted from mitigating negative effects to reinforcing positive ones. This result needs to be discussed against the macro background of China's land marketization reform since the 21st century. Market-oriented reforms in transition economies are usually top-down and incremental, and China's land marketization reform is no exception. In the early stage of land marketization reform, due to limited market mechanisms and strict government control (Chen et al. 2024, Liu et al. 2016), land finance's driving role for urban expansion was hard to exert, and spatial dominance mainly served to mitigate negative effects. As local governments' dependence on land finance increased and the land transfer market matured (Fan, Qiu, Sun 2020), urban

expansion began to shift from disorderly expansion to systematic development. At this point, spatial dominance played a more significant role in reinforcing positive effects.

5.4. Policy implications

The following policy implications emerge from the research findings: Firstly, implement zoned regulation to tackle the widening regional disparity. On the one hand, in the eastern coastal regions, exploring the piloting of property taxes could be considered as a potential measure to cool down the real estate market. This would pressure local governments to reduce their reliance on land based fiscal revenues. Also, machine learning algorithms and big data platforms can strengthen satellite remote sensing monitoring. Based on this monitoring, the approval of land supply indicators for fast-expanding cities should be strictly scrutinized or restricted. On the other hand, in the central and western inland regions, the land revenue reliance rate and land use efficiency indicators should be gradually incorporated into the cadre promotion assessment system. This would drive restrictions on inefficient land development. Additionally, transit-oriented-development based integrated urban and industrial development model projects should be created to provide a replicable and referenceable approach for effective urban expansion.

Secondly, establish a polycentric collaborative governance network to address the spatiotemporal shift. In mature city clusters such as the Yangtze River Delta, Pearl River Delta, and Beijing-Tianjin-Hebei regions, a cross regional trading mechanism for construction land indicators should be explored. Meanwhile, an assessment system for policies on regulating the surplus indicators of urban-rural construction land readjustment should be established. This would coordinate the allocation of land resources across cities within the cluster. Also, fostering a "provincial capital-sub regional center" dual core structure could be beneficial in inland regions. Collaborative efforts in building regional core industrial parks and high-speed rail hubs would curb the inefficient expansion of secondary cities and guide the formation of locally distinctive intensive land use models.

Finally, coordinate the complex system through targeted policies at key nodes. Specifically, when the land revenue reliance degree or expansion rate of a city reaches a certain threshold, targeted intervention measures might be warranted. These could include requiring a certain proportion of rental housing, strictly limiting the supply of commercial land at the urban fringe, and increasing the plot ratio of industrial land. Furthermore, third party assessments of intervention policies should be introduced to dynamically update the key threshold parameters annually.

5.5. Limitations

This study also has some limitations: first, the independent and dependent variables in this study are derived from statistical yearbook data, which can ensure the authenticity and accuracy of the data, but there is also the problem of too much missing data, and future research can be verified by using multiple sources of data such as NPP–VIIRS nighttime lighting data and LandScan population data. Second, although this study used generalized additive model to plot the fitting curves based on the XGBoost-GeoShapley model, it only analyzed the nonlinear relationship between land finance and urban expansion, and future studies can consider further exploring the conditional nonlinear relationship under different variable scenarios. Third, this study used data at the prefecture-level city level, so the sample size is small and may not be able to maximize the advantages of the GeoXAI framework, and future research can further refine to the county level to enhance model effectiveness and explanatory power.

6. Conclusions

Using the panel data of 204 prefecture-level cities in China for the years 2005, 2010, 2015, and 2020, we integrated GeoXAI with traditional econometric models. This approach enabled us to investigate the spatiotemporal characteristics of land finance and urban expansion, as well as the nonlinear relationship and spatiotemporal dynamics between them. The results indicate that in terms of temporal evolution, both land finance and urban expansion in China's prefecture-level cities have shown sustained growth, accompanied by an expansion of regional disparities. Furthermore, a 1% increase in land finance leads to a 0.091% increase in urban expansion. land finance's contribution to explaining the urban expansion model is 6.3%, and there is a complex nonlinear relationship between the two. Through the visualization of GeoShapley values, it is revealed that the impact of land finance on urban expansion has transitioned from negative to positive and continues to strengthen. High-positive-effects are concentrated in second-tier cities and are spreading from the coastal to the inland. Additionally, the spatially positive correlation areas expanded continuously, and spatial interactions have shifted from mitigating negative impacts to reinforcing positive ones. Based on these findings, we propose several policy insights, including implementing zoned regulation to address widening regional disparities, establishing a polycentric collaborative governance network to tackle spatiotemporal shifts, and coordinating complex systems through targeted policies at key nodes.

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Study on interpretation system of world geopark based on tourists' needs and preferences: A case study of Dali Mount Cangshan Global Geopark, Yunnan, China

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ABSTRACT This study takes the Cangshan World Geopark as the research object, focusing on the needs and preferences of tourists. Through a questionnaire survey method, 562 valid samples were collected, and the principal component analysis method was used to systematically explore tourists' preferences for the service types, thematic information, and media forms of the geological park interpretation system. The study found that tourists have significantly higher preferences for basic park guide services, natural environment-related interpretation themes, and multimodal audio-visual interpretation media. They also have dual needs of geological science popularization and local culture experience. Optimizing the interpretation system that meets tourists' needs can not only enhance tourists' geological park tour experience and knowledge acquisition efficiency, but also strengthen tourists' awareness of geological heritage protection and local culture identification, thereby promoting the sustainable development of ecological tourism and community support in world geological parks.

KEY WORDS geopark – visitor demand and preference – interpretation system – principal component analysis method – questionnaire survey

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1. Introduction

World Geoparks, as the core carrier for the protection of geological heritage, popularization education and regional development, its functions highly depend on an efficient Interpretation system (UNESCO 2021). Geotourism, as a specialized tourism form focusing on the appreciation of geological relics and the dissemination of scientific knowledge, has become an important growth point of global ecotourism (Dong, Liu 2015). The Interpretation system, as a bridge connecting tourists and the value of geological heritage, directly determines the depth of tourists' cognition, the quality of their experience and the effectiveness of their protection awareness cultivation. The Cangshan Mountain in Dali was included in the World Geopark list in 2014, making it the second World Geopark in Yunnan Province and a core tourist destination in Dali. Its ecological tourism revenue accounts for 90% of the park's total income. Visitor management is mainly carried out through soft and hard methods: soft management relies on information carriers such as display screens, signs, and mobile apps, while hard management is achieved through facilities such as visitor centers, viewing platforms, and walkways. Currently, only the geological heritage exhibition hall of Cangshan Mountain has systematic Interpretation facilities such as electronic display boards, scenic area models, and manual explanations. The facilities of the two tourist centers, Qionglongnu Pool and Xiamatian Pool, only remain at the basic display screen and photo display level, which is difficult to meet tourists' deep needs for geological knowledge and cultural connotations. In existing studies, discussions on the Interpretation system of heritage mostly focus on a single design principle or specific group preferences (Zhou et al. 2023), lacking systematic empirical analysis that combines the characteristics of geotourism and the heterogeneity of tourists, especially insufficient targeted research on mountainous geological parks in the southwest region. Therefore, accurately identifying the Interpretation needs and preferences of tourists based on their perception becomes the key to optimizing the service system of Cangshan World Geopark and promoting the sustainable development of geotourism.

This study integrates the theories of tourist experience, perceived value, and information processing to construct an analytical framework of "perception – preference – behavior", aiming to address the fragmentation of theoretical application in existing research. At the same time, using the Cangshan World Geopark as a case, it supplements empirical data on mountainous-type geoparks, enriching the research results in the intersection of geological tourism and the Interpretation system, and providing support for cross-regional comparative studies.

Clarifying the preference characteristics of tourists for Interpretation services, themes, and media can provide direct basis for optimizing the existing interpretation system and improving service quality in Cangshan World Geopark. The

research results can guide the park to balance scientificity and entertainment, as well as the application of traditional media and modern technology, thereby enhancing tourists' awareness of geological protection and cultural identity, and promoting the sustainable operation and community development of the geopark.

This study follows a logical sequence of "theoretical support – empirical analysis – conclusion optimization": Firstly, it reviews the core theories and the related research progress of geological tourism and the Interpretation system; Secondly, it collects data through questionnaires and uses principal component analysis to identify the factors influencing tourists' preferences; Finally, based on the results, it discusses the existing problems and proposes targeted optimization strategies.

2. Theoretical foundation and literature review

2.1. Theoretical support for tourism experience

The tourist experience theory (Pine, Gilmore 1999) states that the core of tourism experience lies in creating unforgettable memories through multi-sensory stimulation and interactive design. In the context of a geological park, the Interpretation system serves as the experience carrier, and it needs to balance the professionalism of geological knowledge with the Entertainment value of the presentation form – by integrating visual, auditory, and other multi-sensory elements, complex geological processes can be transformed into perceptible content, helping tourists form a deep experience (Chen et al. 2022). This theory provides a core perspective for the analysis of tourists' preferences for interpretation media and activity participation in this paper. The perception value theory (Zeithaml 1988) defines perception value as the comprehensive evaluation by tourists of the functional value and emotional value of the product. For the Interpretation system of the geological park, the functional value is reflected in the acquisition of practical information such as geological knowledge and tour guidance, while the emotional value stems from cultural resonance and aesthetic pleasure (Huang et al. 2023). Research shows that tourists' preferences for the interpretation system are essentially an attempt to balance these two types of values, and this theory provides support for analyzing the logic of tourists' choices regarding information content and presentation methods. The information processing theory (Atkinson, Shiffrin 1968) emphasizes that the presentation method of information directly affects the retention of memory and the depth of understanding by the audience. In geological interpretation, the integration of multimodal information (text, audio, interaction) can significantly enhance the perceptual fluency of tourists (Chen 2022), while the excessive use of technical terms can lead to cognitive obstacles

(Zhao 2024). This theory provides a theoretical basis for analyzing the preference differences among different media types and optimizing information presentation in this paper.

2.2. Relevant research progress

The United Nations Educational, Scientific and Cultural Organization (UNESCO 2022) defines the Interpretation System of Geological Parks as "a comprehensive information system that conveys the scientific value, aesthetic features, and cultural significance of geological heritage to the public through various media", with its core functions covering scientific education, cultural narrative, and experience enhancement. In domestic research, Zhou et al. (2023) proposed a three-dimensional model of "content – medium – perception", emphasizing that the system needs to balance scientific accuracy and entertainment value; Ke and Liu (2019) through grounded theory research found that tourists' demands for geological interpretation present a progressive feature of "knowledge acquisition – emotional resonance – behavioral transformation".

The core attraction of geological tourism lies in the uniqueness and educational value of geological relics (Dong, Liu 2015). In foreign studies, Chen (2010) found that there were significant differences in the interpretation styles preferred by Western and Eastern tourists. Western tourists preferred inquiry-based questions, while Eastern tourists were more receptive to conclusion-based knowledge delivery. Liu et al. (2022) pointed out that VR technology has a particularly prominent appeal to young tourists (18–35 years old), but there is a technological acceptance gap among the elderly. Domestic studies mostly focus on single park cases. For example, Huang et al. (2023) took Yunnan Stone Forest as an example and confirmed that cultural integration-based interpretation can enhance tourists' local attachment. However, research on multi-dimensional preferences for mountainous geological parks is still scarce.

Geological interpretation is the core component of geological tourism, emphasizing the transformation of complex geological scientific knowledge into information that the public can understand. Its quality directly affects the educational value and experience effect of geological tourism (Li et al. 2023).

Recent studies have shown that geological interpretation should be combined with the local cultural context and enhance tourists' emotional resonance through narrative storytelling (Zhang, Pearce 2023); at the same time, the application of digital technologies (such as VR/AR) can break through time and space limitations, allowing tourists to intuitively experience the geological evolution process (Chen et al. 2022). However, existing research pays insufficient attention to the differentiated strategies of interpretation for different types of geological parks, and

lacks a systematic analysis of tourists' interpretation preferences in mountainous geological parks.

The current research has three shortcomings: Firstly, the application of theories is fragmented, lacking a systematic integration of multiple theories; Secondly, the regional cases are unbalanced, with relatively few empirical studies on mountainous geological parks in the southwest region; Thirdly, the literature support is single, with insufficient citation of the latest frontier achievements in geological tourism and geological interpretation, mostly relying on UNESCO documents and local literature, and lacking dialogue with international cutting-edge research.

3. Research design and methods

3.1. Research site

The Cangshan World Geopark is located in Dali City, Yunnan Province, China (Fig. 1). It borders Yongbing County and Erlian County. The total area is 520 square kilometers, with a length of 50 kilometers from north to south and 10–20 kilometers from east to west. Cangshan is a landmark mountain peak with distinctive

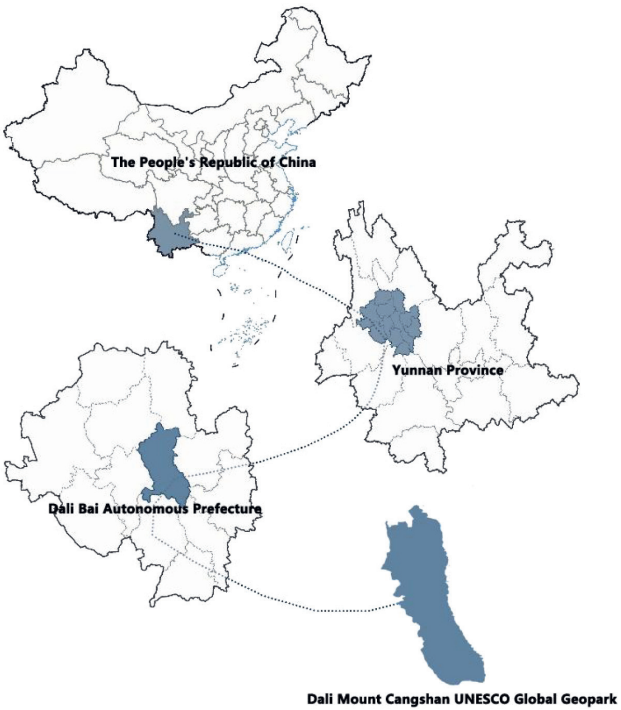


Fig. 1 – Location of Dali Mount Cangshan UNESCO Global Geopark

Tab. 1 – Demographic statistical characteristics of samples

Demographic characteristics	Outcome
Gender	47.5% male, 52.5% female
Age	The average age is 39.3 years
Mother tongue	Chinese (92%), English (8%)
Place of residence	Yunnan (38%), Sichuan (27%)
Total annual income	> 60,000 yuan (40%)
Number of co-visitors	The average is 3.4 people
Residence time	3.2 nights on average
High school degree or above	90.9% (511)

features, unique geological wonders, and potential special geological scientific value. Its special geography, geology, and landforms have created a natural landscape combining mountains and water, with wind, flowers, snow, moon, and stones coexisting. Cangshan belongs to the southern end of the Yunling Mountains in the Xiangdong Mountain Range. It is an important geological, geographical, biological, and climatic transition zone in China and Southeast Asia, and is a landmark area in regional division. The east side of Cangshan is Erhai Lake. Cangshan and Erhai Lake complement each other, which is the result of the difference in crustal uplift (Huang et al. 2018).

3.2. Sampling strategy and sampling error

This study employed a non-probability sampling method. The survey period was from June to September 2024. Electronic questionnaires were distributed to tourists visiting the Cangshan World Geopark. According to the sample size calculation standard of Krejcie, Morgan (1970), when the total population exceeds 1 million, the minimum sample size at a 5% precision level is 384. This survey collected a total of 562 questionnaires, and the effective recovery rate met the research requirements. The respondents of the questionnaire could be summarized as 47.5% males and 52.5% females, with an average age of 39 years old. The majority of the respondents were domestic tourists, accounting for 92%, and most came from the southwestern provinces of China. The average stay time in Dali was 3.2 nights, and the average number of visits to the park was 1.4 times (Table 1).

3.3. Questionnaire design

The questionnaire consists of three parts: The first part covers demographic characteristics and basic tourism information, including gender, age, education level,

income, and duration of stay; the second part is the Interpretation Preference Survey, which includes 14 service preferences, 18 thematic information preferences, and 18 media preferences, using a 5-point Likert scale (1 = strongly disagree / not important at all, 5 = strongly agree / extremely important). The variables in this part are based on the specific features of the park, such as the park's flora and fauna, geological features, cultural characteristics, and the World Geopark Heritage List. The third part presents the overall evaluation by tourists of the significance of the Interpretation service. The questionnaire was designed based on the park's characteristics and existing research results. After a pre-survey (with a sample size of 50) and revision, it ensured content validity and readability.

3.4. Data processing methods and model construction

The research will place the data obtained from the survey into Microsoft Excel, and then conduct statistical analysis using the social science statistical software SPSS. The data analysis consists of three stages: In the first stage, descriptive results (such as age, gender, native language, and place of residence) of the data will be analyzed, revealing the demographic statistics profile of these visitors; In the second stage, principal component analysis will be conducted on 14 Interpretation service preference items, 18 preference themes and information items, 18 themes and information range items, and skew rotation and Kaiser normalization will be performed, and 18 preferred media items will be considered to improve the interpretability of each factor structure. Among them, the KMO test measures a value > 0.7, which is considered acceptable (Bartels, Orenburg, Giao 2007). Therefore, all factors with eigenvalues greater than 1 were used, and all items with factor loadings > 0.3 were regarded as contributing to the factor structure. Items with factor loadings > 0.4 and cross-loadings onto two factors were classified as the best interpretable factors. All factors with Cronbach's α coefficient higher than 0.6 and item correlations between 0.15 and 0.55 were considered acceptable reliability indicators. Factor scores are calculated as the average of all items contributing to a specific factor, for interpretation on the applicable five-point Likert scale.

Principal component analysis is an attempt to combine many original indicators (such as P indicators) with certain correlations into a set of new uncorrelated composite indicators to replace the original indicators. It is a multivariate statistical method for studying the correlations between multiple variables, and it studies how to reveal the internal structure of multiple variables through several principal components, that is, to derive several principal components from the original variables to retain as much information as possible. Usually, the original *P* indicators are linearly combined to form the new composite indicators (Wang et al. 2021).

It is represented by the variance of F_1 (the first linear combination, that is, the first composite index), that is, the larger the VaR (F_1), the more information F_1 contains. Therefore, the F_1 selected from all linear combinations should have the maximum variance, so F_1 is called the first principal component. If the first principal component is not sufficient to represent the information of the original P indicators, then consider selecting F_2, that is, the second linear combination. To effectively reflect the original information, the existing information of F_1 does not need to appear in F_2. In mathematical language, cov (F_1, F_2) = 0, then F_2 is called the second principal component. By analogy, the third, fourth, ..., and the P_{th} principal components can be constructed. The steps are as follows:

$$F_p = a_{1i} \times ZX_1 + a_{2i} \times ZX_2 + \ldots + a_{pi} \times ZX_p \quad (1)$$

where a_{1i}, a_{2i}, ..., a_{pi} ($i = 1, \ldots, m$) are the eigenvectors of the covariance matrix ∑ eigenvalues of X, corresponding to ZX_1, ZX_2, ..., ZX_p are the normalized values of the original variables.

$$A = (a_{ij})\ p \times m = (a_1, a_2, \ldots, a_m),\ Ra_i = \lambda_i a_i \quad (2)$$

R is the correlation coefficient matrix, λ_i and a_i are the corresponding eigenvalues and unit eigenvectors, $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p \geq 0$.

4. Research results

4.1. Interpretation service preference principal component analysis

Through principal component analysis, the preferences of tourists for Interpretation services were extracted into three common factors (Fig. 2). Respondents indicated that they needed park guides (Factor 1), activity participation (Factor 2), and information structure (Factor 3) to obtain a high-quality park tourism experience. The cumulative variance explained by all three factors was 56.4%, and the Cronbach's α coefficients of each factor were all > 0.75, with the inter-item correlation being higher than 0.42. The reliability was good (Table 2). A factor loading of 0.30 was considered significant, while a factor loading of 0.50 was considered very significant (Chen et al. 2022).

Factor 1 (park guide): Average score 4.28, including tourist route signs, park rules brochures, staff consultations, free maps, etc. The factor load is between 0.503 and 0.831, and it is the service type that tourists value the most; Factor 2 (activity participation): Average score 3.47, covering food experiences, science popularization film screenings, local culture experiences, and related book sales, etc. The factor load is between 0.449 and 0.807; Factor 3 (information structure): Average score 4.05, including digital display of geological relics, digital

Tab. 2 – Interpretation services preferred by visitors

	Pattern matrix Variance 56.4%	Component factors		
		Factor 1	Factor 2	Factor 3
Park guide	Information on park rules and regulations that can be clearly communicated, such as trail signs and pamphlets	0.831	—	—
	Clear directions to the park (e.g. rest areas, tour times)	0.742	—	—
	Park staff who are able to answer most questions, both general and professional	0.747	—	—
	Information and activities about the park should be displayed on the website	0.614	—	—
	A map of the park at no extra cost	0.503	—	—
Event participation	Culinary experiences (e.g. game dishes or local cultural dishes)	—	0.795	—
	Activities (e.g. nature, culture and education, popular science film screenings, photography)	—	0.807	—
	Experience the lifestyle of a local culture or community	—	0.769	—
	Magazines, books, and newspapers on the Geopark environment and geological heritage are sold	—	0.634	—
	A guide to digital interaction systems	—	0.449	—
Information structure	A digital display of the geological heritage release	—	—	0.856
	A digital display of the viewing platform in the park	—	—	0.724
	Animal and plant identification information (e.g., species name, species information)	—	—	0.751
	An information board for the day's scene	—	—	0.627
Kronbach coefficient		0.775	0.784	0.756
Average value		4.28	3.47	4.05
Inter-project dependencies		0.437	0.422	0.454
Methods: Principal component analysis				



Fig. 2 – Heatmap of the correlation among Interpretation service's influencing factors

Tab. 3 – Topics required for the interpretation center

	Pattern matrix Variance 58.26%	Component factors	
		Factor 4	Factor 5
Heritage	The geological heritage of the park	0.856	—
	The cultural and community context surrounding the park	0.821	—
	History of the park	0.775	—
	The significance of the historical and cultural city in the park	0.744	—
	The significance of the park as a global geopark	0.728	—
	Dali Bai (such as the history, culture and lifestyle of the Bai people)	0.677	—
	Other related attractions in the park (e.g. Erhai Lake, Shimen Pass, etc.)	0.632	—
	The status of parks in China's geoparks	0.473	—
	The archaeological value of the park (e.g. historical sites of the Nanzhao Kingdom and the Dali Kingdom)	0.459	—
Natural	Ecological environment of the park (relationship with the surrounding environment)	—	-0.855
	Climate of the park (climate and weather of the park)	—	-0.832
	Animals of the park (e.g. birds, insects, mammals, carnivores)	—	-0.840
	Plants of the park (e.g. trees, flowers, shrubs, etc.)	—	-0.775
	The geography of the park (i.e., the physical characteristics of the park's earth and atmosphere)	—	-0.753
	Hydrogeography of the park (i.e. water movement in the park, water quality and impacts of the water system in the park)	—	-0.687
	Practical issues about environmental modification (e.g. recycling technology or water conservation)	—	-0.454
	Celestial observations (e.g. stargazing) in the park	—	-0.471
Kronbach coefficient		0.883	0.875
Average value		4.08	4.36
Inter-project dependencies		0.473	0.528
Methods: Principal component analysis			

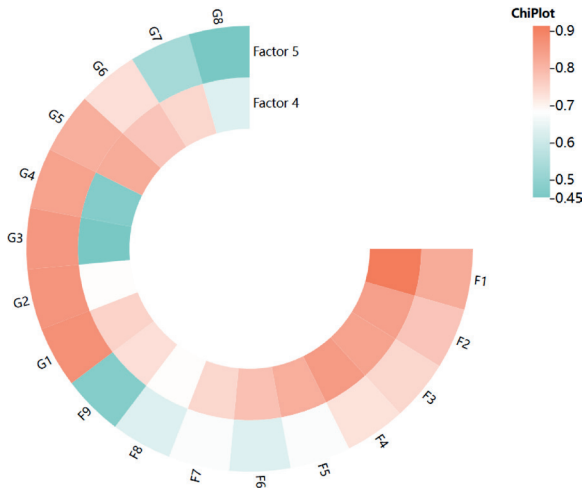
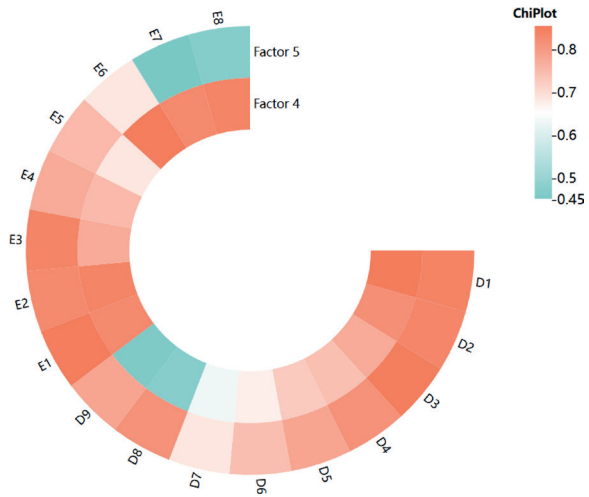


Fig. 3 – Heatmap of information relevance

Tab. 4 – Breadth of information contained in the interpretation center

	Pattern matrix Variance 57.12%	Component Factors	
		Factor 4	Factor 5
Heritage	The geological heritage of the park	0.915	—
	The cultural and community context surrounding the park	0.843	—
	History of the park	0.836	—
	The significance of the historical and cultural city in the park	0.851	—
	The significance of the park as a global geopark	0.817	—
	Dali Bai (such as the history, culture and lifestyle of the Bai people)	0.784	—
	Other related attractions in the park (e.g. Erhai Lake, Shimen Pass, etc.)	0.745	—
	The status of parks in China's geoparks	0.687	—
	The archaeological value of the park (e.g. historical sites of the Nanzhao Kingdom and the Dali Kingdom)	0.732	—
Natural	Ecological environment of the park (relationship with the surrounding environment)	—	0.874
	Climate of the park (climate and weather of the park)	—	0.865
	Animals of the park (e.g. birds, insects, mammals, carnivores)	—	0.858
	Plants of the park (e.g. trees, flowers, shrubs, etc.)	—	0.837
	The geography of the park (i.e., the physical characteristics of the park's earth and atmosphere)	—	0.815
	Hydrogeography of the park (i.e. water movement in the park, water quality and impacts of the water system in the park)	—	0.732
	Practical issues about environmental modification (e.g. recycling technology or water conservation)	—	0.536
	Celestial observations (e.g. stargazing) in the park	—	0.454
Kronbach coefficient		0.928	0.917
Average value		3.95	4.13
Inter-project dependencies		0.672	0.614
Methods: Principal component analysis			

Fig. 4 – Heatmap of topic relevance



presentation of viewing platforms, and identification information of animals and plants, etc. The factor load is between 0.627 and 0.856.

4.2. Information and topic principal component analysis

In Tables 3 and 4, respondents rated two aspects: what information (i.e., topics) the Interpretation center should provide and the extent to which they expect to obtain specific topic information in the Interpretation. Both aspects include two factors: heritage (Factor 4) and natural environment (Factor 5). The Cronbach's α coefficients of both factors are higher than 0.8, and the inter-item correlation is higher than 0.4.

The topic preference analysis (Fig. 3, Table 3) extracted two factors: heritage (Factor 4) and natural environment (Factor 5). The cumulative variance explained rate was 58.26%, with α coefficients both > 0.88, indicating excellent reliability: Factor 4 (heritage): average score 4.08, covering geological relics, cultural community background, historical evolution, Bai ethnic culture, etc., factor loadings 0.459–0.856; Factor 5 (natural environment): average score 4.36, including ecological environment, climate, flora and fauna, geographical and hydrological information, factor loadings 0.454–0.855. These are the most concerned topic categories by tourists.

The information breadth preference analysis (Fig. 4, Table 4) extracted two common factors, with a cumulative variance explanation rate of 57.12%, and the α coefficients were all > 0.91, indicating excellent reliability. The average score of heritage-related information was 3.95, with factor loadings ranging from 0.687 to 0.915. The average score of natural environment-related information was 4.13, with factor loadings ranging from 0.454 to 0.874, which was consistent with the results of the topic preference, and the demand for natural environment-related information was higher than that for heritage-related information.

4.3. Interpretation of media components analysis

The study analyzed the interpretation of the required media for the park and presented the results in Table 5 and Figure 5. Interpretation of media extracted three common factors, with a cumulative variance explanation rate of 64.28%, and the α coefficients were all greater than 0.68, indicating acceptable reliability (Table 5): Factor 6 (audio and visual): The average score is 3.58, including audio and visual media, visual images, prop displays, audio playback, 3D displays, VR experiences, etc. The factor loadings range from 0.475 to 0.837, making it the most preferred type of media; Factor 7 (creative text): The average score is 3.29, covering concise

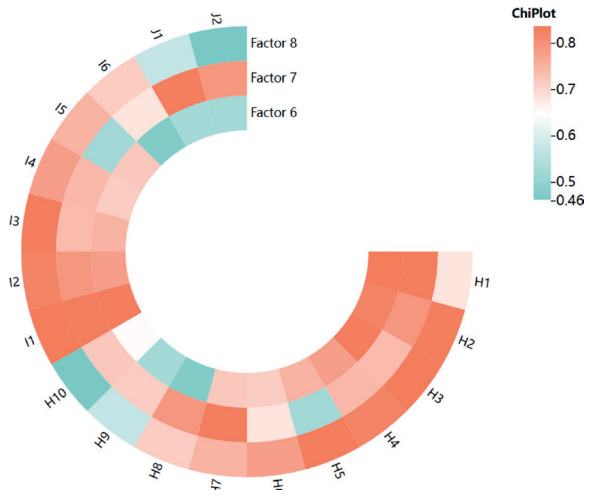


Fig. 5 – Heatmap of interpretation media relevance

and understandable texts, non-academic expressions, game-like media, etc. The factor loadings range from 0.524 to 0.834; Factor 8 (connection): The average score is 2.34, including commemorative merchandise sales, life-like size displays, etc. The factor loadings range from 0.463 to 0.571, with the lowest preference.

5. Discussion

This study takes the Cangshan World Geopark as a case, using the principal component analysis method to systematically identify the tourists' preferences for the geological park's interpretation system in terms of service, theme, and medium. The research results not only confirm the common patterns in the field of geological tourism, but also reveal the unique demand characteristics of mountainous and culturally integrated geological parks. This section combines the relevant research results on geological tourism and geological interpretation to deeply analyze the formation reasons and practical connotations of tourists' preference characteristics, compares the similarities and differences between this study and existing research, and points out the limitations and future research directions of this study, providing theoretical and empirical support for the optimization of the geological park's interpretation system.

The tourists' preference for park guide services ranks first (average 4.28), which is highly consistent with the conclusion proposed by Liu et al. (2023) that "tourist convenience is the fundamental guarantee of the tourism experience". As a mountainous geological park, Cangshan has a wide scenic area and complex terrain, and tourists have an inevitable demand for clear tour routes, rule notifications, and

Tab. 5 – Important media required for interpretation at the DMCUGG visitor center (interpretation center)

	Pattern matrix Variance 64.28%	Component factors		
		Factor 6	Factor 7	Factor 8
Audio and visual	Audiovisual media (e.g. videos explaining the history of the Geopark)	0.837	—	—
	Visual media (e.g. pictures and charts showing interesting information about the Geopark)	0.824	—	—
	Displays of props or objects (e.g. archaeological, plant, insect, or cultural displays)	0.836	—	—
	Audio media (such as bird or animal sounds)	0.781	—	—
	2D display (e.g. park information poster)	0.752	—	—
	3D displays (e.g. life-size examples of animals, cultural artefacts, or virtual tours)	0.715	—	—
	Print media (e.g. brochures and posters with interesting information for visitors, interpretation centers)	0.721	—	—
	Virtual reality (e.g. a virtual tour of a traditional local house)	0.475	—	—
	Smart media (interactive touch screens with information of interest to visitors)	0.527	—	—
	Guided tour of the Interpretation Center for Tourists	0.656	—	—
Creative Texts	Easy-to-read text and information in relevant media (e.g., appropriate fonts)	—	0.834	—
	None of the media uses technical or academic jargon (for ease of understanding)	—	0.793	—
	All mediums are presented in a concise manner		0.739	
	Expressions in all media should be lively, rich, lively, and exciting	—	0.742	—
	Game-based media (e.g. quizzes, puzzles)	—	0.524	—
	The staff in the Visitor Interpretation Center need to be able to answer all questions on display	—	0.684	—
Contact	The Interpretation Center sells souvenirs as memories of the experience	—	—	-0.571
	The size of the monitor and media should show the size of everyday life in order to better convey the relevant information	—	—	-0.463
Kronbach coefficient		0.904	0.843	0.687
Average value		3.58	3.29	2.34
Inter-project dependencies		0.526	0.488	0.482
Methods: Principal component analysis				
Rotation method: maximum oblique rotation				

free maps, etc., as these services are necessary for tourists to conduct in-depth tours and obtain geological and cultural information. The high preference for information structure services (average 4.05) reflects the core demand of digital era tourists for visualized and convenient geological information. Mountainous geological parks have geological relics distributed outdoors, and digital display can break through time and space limitations, allowing tourists to obtain geological

relics, viewing platforms, flora and fauna and other related information at any time during the tour, which is in line with the viewpoint in information processing theory that "multiple scenarios of information access enhance perceptual fluency" (Wang, Wang 2025). The preference for activity participation services is relatively low (average 3.47), not because tourists lack experience needs, but due to the limitations of existing service design and tour scenarios. The ecological tourism of Cangshan is mainly outdoor, and tourists' stay times are scattered. However, existing cultural experiences and science popularization activities are mostly concentrated in the tourist center, with a relatively simple form, which is difficult to match the outdoor tour rhythm of tourists. At the same time, the transportation and venue conditions of mountainous scenic areas also limit the implementation of interactive activities, and this result also provides a clear direction for the subsequent optimization of activity design and the creation of mobile experience projects in the park.

The preference for natural environment-related themes is significantly higher than that for heritage themes (mean 4.36 vs 4.08). This is the result of the joint influence of the resource characteristics of Cangshan Geopark and the tourists' travel motivations. As an important geological, biological and climatic transition zone in Southeast Asia, Cangshan has a unique ecological environment, hydrological geography, animal and plant resources and geological relics that deeply intermingle. The tourists' travel motivations include both geological science popularization and natural landscape appreciation. The high demand for natural environment-related information essentially reflects the tourists' urgent need to understand the "natural background" of the geological park. While heritage-related themes still maintain a relatively high preference, it reflects the "cultural empowerment" feature of geological tourism. The Bai ethnic culture, the history of the Nanzhao-Dali Kingdom and the geological relics in Cangshan form a unique "geological-culture" symbiotic system. The tourists' demand for such information reflects the transformation of the geological park's interpretation system from a single scientific dissemination to a "science + culture" integrated narrative (Zhao et al. 2019), which is in line with the cutting-edge viewpoint proposed by You et al. (2026) that "heritage interpretation should be combined with the local cultural context". From the perspective of information breadth preference, the high scores for natural environment and heritage-related information (mean 4.13, 3.95) indicate that tourists' information needs for the geological park are not fragmented but have systematic and comprehensive characteristics. This requires the content design of the interpretation system to balance the depth and breadth of information, achieving the organic integration of natural and cultural information.

Audio and visual media have become the tourists' top choice (mean 3.58), confirming the core value of multi-modal information integration in geological interpretation (Xia 2013). The geological relics in Cangshan, such as Quaternary

glacial deposits and fault structures, have complex formation processes and temporal-spatial characteristics. Simple textual explanations are difficult to enable tourists to intuitively understand them. However, multi-modal media such as audio-visual media, 3D displays, VR experiences, etc., can transform abstract geological processes into visual and auditory experiences, breaking through the cognitive barriers of geological science. At the same time, the outdoor tour scenarios of mountain-type geological parks also determine that tourists prefer intuitive and convenient visual media rather than lengthy textual information. The medium with medium preference (mean 3.29) emphasizes the core principle of geological interpretation being "popularization and entertainment". Li et al. (2025) pointed out that the relationship between professional terms in geological interpretation and tourists' understanding degree is an inverted U-shaped curve. The results of this study further verify this viewpoint – tourists need concise and understandable text expressions without academic terms, even preferring game-like media and other entertaining forms. This requires the geological park interpretation system to ensure scientificity while also considering the readability and entertainment value of the information. The lowest preference for associative media (mean 2.34) is due to the weak correlation between carriers such as souvenirs and the core goal of geological interpretation. The tourists' core needs are immediate knowledge acquisition and experience improvement, rather than commemorative consumption. Such media can only serve as supplementary to the interpretation system rather than a core component.

The results of this study effectively echo and complement the existing research in the fields of geological tourism and geological interpretation. Consistent with the conclusion of Yang and Zhu (2023) that "digital media is favored by tourists", this study further reveals that tourists in mountain-type geological parks have more scene-specific demands for digital media, and are more inclined towards mobile and visual digital media that can match outdoor tours, rather than being limited to fixed digital facilities in tourist centers. The sample of this study is mainly composed of domestic tourists (92%), and their preferred "conclusion-based" knowledge transmission method conforms to the cognitive habits of Eastern tourists, which provides a targeted basis for the expression style of geological park interpretation content – prioritizing the presentation of clear geological scientific conclusions, followed by in-depth exploratory content, while balancing the efficiency and depth of popularization. At the same time, this study takes Cangshan Mountain as the case of a mountain-type geological park, revealing the uniqueness of tourists' preferences in such parks, such as a higher demand for basic guided tours and the urgent need for outdoor digital interpretation, enriching the case library of tourists' preferences in geological parks and providing differentiated references for the design of interpretation systems for different types of geological parks.

Although this study has achieved certain empirical results, it still has three limitations: Firstly, the sampling method used is non-probability sampling, and the samples mainly come from western provinces such as Yunnan and Sichuan. The geographical representativeness is limited, and it fails to cover different regional and different tourism motivation groups of tourists, which may affect the generalizability of the research results. Secondly, it did not deeply analyze the moderating effect of tourists' heterogeneity on preferences, such as the correlation between demographic characteristics like age and educational background and tourists' preferences, making it difficult to achieve precise design of the interpretation system. Thirdly, it only identified tourists' preference characteristics, but did not explore the matching issue of media and themes, that is, which media form is suitable for different interpretation themes (such as geological relics, Bai ethnic culture), lacking precise guidance for the design of the interpretation system. In response to these limitations, future research can be conducted in three aspects: Firstly, adopt stratified probability sampling method to expand the geographical and group scope of the sample, and enhance the universality of the research results; Secondly, introduce structural equation models, regression analysis, etc., to explore the influence mechanism of tourists' heterogeneity on the preferences of the interpretation system, reveal the differences in the needs of different groups, and provide a basis for precise interpretation services; Thirdly, conduct research on the matching of media and themes, through experimental methods and in-depth interviews, identify the optimal media presentation form for different interpretation themes, and achieve refined and personalized design of the geological park interpretation system; In addition, it can also conduct research on the effectiveness verification of the optimization of the interpretation system, by comparing the tourists' experience and knowledge acquisition efficiency before and after optimization, to test the effectiveness of the optimization strategies.

6. Conclusions

This study focused on the Geopark of Cangshan Mountain, taking the tourists' perception as the entry point. Through questionnaire surveys, 562 valid samples were collected. Using the principal component analysis method, the study systematically explored the tourists' preferences for the geological park's interpretation system in terms of service, theme, and medium. The following core conclusions were ultimately drawn:

1. In terms of service preferences, tourists showed the characteristics of "prioritizing basic guided tours, having a strong need for digital information structure, and needing to optimize experience activities". The basic service of park guides is the core demand of tourists. The digital display of geological and

landscape information has become an important necessity. However, cultural experiences and science popularization activities have not yet met the tourists' needs due to design and scene limitations.
2. In terms of theme preferences, tourists prioritize information related to the natural environment, while also having a demand for the integration of geological heritage and local culture. The demand for natural and cultural information is characterized by systematicness and comprehensiveness, reflecting the integration trend of "science + culture" in geological tourism.
3. In terms of medium preferences, tourists highly favor multimodal audio-visual media. They also require the popularization and entertainment of the interpretation text and consider commemorative items as supplementary, which cannot become the core interpretation medium.
4. Overall, the interpretation needs of tourists in Cangshan Mountain present the characteristics of "balancing scientificity and entertainment, balancing professionalism and popularization, and integrating traditional forms with modern technology". And influenced by the resource characteristics and tour scenarios of mountain-type geological parks, the requirements for the convenience of services and the scene adaptability of media are higher.

Based on the empirical conclusion of tourists' preferences, combined with the resource characteristics of the Cangshan World Geopark and the existing problems of the interpretation system, targeted optimization strategies are proposed from four dimensions: popular science education, interpretation system, tourism products, and service facilities, to achieve precise matching between the interpretation system and tourists' needs:

Deeply explore the scientific connotation of the geological relics on Cangshan, sort out the internal connections of geological evolution, tectonic movement, and ecological environment, and compile scientific and popular science popularization materials that are both scientific and easy to understand, avoiding excessive use of professional terms; combine modern technologies such as VR and AR to create immersive geological popularization experience projects, such as VR simulation of the formation process of glacial deposits and AR visualization display of fault structures, allowing tourists to intuitively experience the complex geological process; rely on the outdoor geological relics of the park, carry out regular on-site geological exploration and popular science lecture activities, invite geological experts and local cultural scholars to participate in the explanation, achieving the integration and dissemination of geological science and local culture.

Improve the basic service of the park guide, optimize the design of tour route signs and free maps, add information consultation points at key scenic spots in the scenic area, and enhance the professional answering ability of staff; build a "online + offline, fixed + mobile" diversified interpretation media system, add

3D display, interactive touch screens and other fixed digital facilities at the tourist center, set QR code interpretation signs beside outdoor geological relics and viewing platforms, realize "listening while walking while looking", matching the tour scenarios of mountainous-type scenic areas; simplify the expression of interpretation texts, adopt a combination of pictures and text, and interesting expression forms, design geological knowledge quizzes, puzzles and other game-like media at some nodes, to enhance tourists' participation.

Based on the "geology + culture" integrated demand of tourists, develop characteristic tourism products that integrate geological science and Bai ethnic culture, such as "geological relics + Bai ethnic village" study tours, "Cangshan geology + Erhai Lake + ecology" comprehensive experience tours, etc. According to the demand characteristics of different tourist groups, design differentiated tour routes, for scientific tourists, create deep geological relic exploration routes, for leisure tourists, create "geological landscape + natural viewing" light experience routes, for parent-child tourists, create interesting geological science popularization routes, achieving precise supply of tourism products.

Upgrade the interpretation facilities of the seven dragon goddess pool and wash horse pond tourist centers, make up for the basic deficiencies of existing facilities, add systematic display areas with geological and cultural themes, achieve complementary functions of the three tourist centers, improve the outdoor infrastructure of the scenic area, add shading, seats and other facilities at rest areas and viewing platforms, combine with simple interpretation display boards, allowing tourists to obtain information while resting, optimize the network coverage of the scenic area, ensure the normal use of mobile digital interpretation media, providing technical support for multi-modal and mobile interpretation.

The results of this study indicate that the interpretation system of a World Geopark is not merely an "information dissemination tool", but a crucial link that connects geological heritage protection, popular science education, tourism experience, and community development. Its design and optimization must adhere to the principles of "centering on the needs of tourists, based on resource characteristics, aiming for scientific dissemination, and empowering through cultural integration", while balancing scientificity and entertainment, professionalism and simplicity, traditional forms and modern technologies. For mountainous geological parks, particular attention should be paid to the convenience of services and the scene-appropriate nature of media, to create an interpretation system suitable for outdoor tourism scenarios. Additionally, the optimization of the interpretation system in a geological park is a dynamic and continuous process. A long-term monitoring mechanism for tourists' needs should be established to promptly capture changes in tourists' demands and continuously adjust and optimize the content, form, and carriers of interpretation. Only by making the interpretation system truly meet the needs of tourists can its core functions of popular science

education, experience enhancement, and cultural dissemination be fully exerted, promoting the coordinated improvement of ecological, economic, and social values of the World Geopark.

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River (non)revitalization: when the human-altered watercourse can be a better choice

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ABSTRACT The outcomes of watercourse revitalization are mostly evaluated as positive, depending on the implementation of the given revitalization. A potential negative aspect of watercourse revitalization was investigated via the example of an important source of groundwater for drinking purposes in Březová nad Svitavou. The aim of the research was to assess whether revitalization of the watercourse in the section upstream of the offtake point was appropriate. The assessment used long-term data from the watercourse operator as well as our own short-term monitoring. The results indicate that in this section, the risk of contamination from surface water into groundwater significantly outweighs other benefits of revitalization. Therefore, a partial, modified revitalization was proposed, which in the assessed section maintains and regenerates the existing separation between the watercourse and the groundwater. At the same time, however, it enables the formation of river sediment in the trough as a natural environment for the development of zoo- and phytobenthos and related higher organisms.

KEY WORDS river revitalization – groundwater – pollution – drinking water source – hyporheic zone – Ústecká syncline

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1. Introduction

Watercourse revitalization is currently one of the main activities of water management, landscape engineering and urban planning with the aim of returning the "degraded" parts of watercourses to their natural state and supporting natural relationships between surface water and water in alluvial and bank zones. The aim is not only to regenerate the basic cycle of water flow in the countryside (Magliozzi et al. 2019) but also to support natural biodiversity of aquatic ecosystems (Durčák et al. 2017). Biotope and morphological watercourse diversity is essential for the stability of aquatic ecosystems, as it enhances the resilience of the biota to extreme environmental events – floods, drought, pollution, etc. (Edwards et al. 2012). Revitalization, accompanied by subsequent landscape modifications, has a positive impact on the landscape water retention capacity, stabilizes ecosystems and contributes to mitigating the overall effects of climate change. (Beran 2022; Rozman, Hrkal 2020). For example, vegetation on the banks and in the immediate vicinity of a watercourse can significantly influence its microclimate by shading the water surface, which enables it to absorb daily temperature extremes (Durčák et al. 2017). Rozman and Hrkal (2020) also mention revitalization as a beneficial tool in the fight against flooding as it naturally slows down the water flow and, in suitable areas, enables a regulated water spill.

Generally speaking, revitalization enables "the return of the river to its natural state". Nevertheless, any watercourse revitalization leads to a significant technical impact on the current water system in the given locality, affecting the current water regime and ecosystem process (Mrozinska et al. 2018, Wood et al. 2023). This tool is often used in those parts of watercourses which have been heavily influenced by human activities (Kurth, Weber, Schirmer 2015). Such watercourses might have been strengthened and their bottoms and banks reinforced with often impermeable surfaces (stone, concrete, etc.). In particular, watercourses in settlements are usually in very poor condition, where the troughs were created completely artificially to adapt to local structures and anti-flood measures, and their natural ecosystems are often severely disturbed (May 2006, Bell 2015). Pollution washed away from the surrounding reinforced surface or from sewage systems also contributes to this (Kožený, Janovská, Svobodová 2021). Revitalization is intended to help remove these maladies and return the area to its natural state, which in many cases can also cope with pollution. However, this is the case only when there is a stable and strong ecosystem in the watercourse.

Troughs influenced by human activities can be found even outside of built-up areas. Such troughs are mainly affected by watercourse alterations in agricultural landscapes, where they are straightened, often even forming a rectangular network in connection to irrigation/amelioration systems. This creates regular landscapes that are easier to manage from an agricultural perspective. Its aquatic

ecosystems are also prone to disruption, which is often caused by the application of chemical spraying to protect plants and application of nitrogen-based fertilizer, which is often washed into watercourses and groundwater (Bridhikitti et al. 2021; Filoso, Palmer 2011; Gumiero, Boz 2017).

In agricultural landscapes, larger revitalizations are relatively more common than in built-in areas since the former naturally enable greater alterations to the watercourse's surrounding landscape. The trough is often spread to the whole inundation area, creating meanders and branching into more troughs together with water surfaces etc. (Beran 2022, Richter 2023). In built-up areas, the watercourses are usually modified within the extent of the troughs/bank edges and the modification is more likely to occur within the existing trough, where artificial impermeable surfaces are replaced with naturally permeable surfaces (Kurth, Weber, Schirmer 2015). It is highly advisable to combine the watercourse revitalization with landscaping around the watercourse, which brings a number of other benefits, such as creation of areas for recreation and relaxation, contamination reduction, etc. (Gumiero, Boz 2017). There are countless examples of revitalizations ranging from small projects of a local nature, comprising tens of meters (Rozman, Hrkal 2020), to large multi-kilometer projects on important watercourses (Vizina et al. 2018). Revitalizations are generally a frequently discussed topic by both professionals and the general public for many reasons. Nevertheless, a positive response to revitalizations prevails. But is watercourse revitalization suitable everywhere?

From an ecological and social perspective, watercourse revitalization is beneficial, it improves the quality of the environment, increases the value of the ecosystem itself and ecosystem services and, moreover, has an aesthetic value (Palmer, Filoso 2009; Shackelford et al. 2013). It always naturally depends on the actual implementation of the revitalization and the defined objective that is to be achieved. A rarely (or hardly ever) discussed issue is the impact of the revitalization on the potential spread of contaminants from polluted water. As aforementioned, water is often contaminated by human activities, especially when settlements, industry and agricultural activities are accumulated in the vicinity of a watercourse (Filoso, Palmer 2011; Gumiero, Boz 2017; Magliozzi et al. 2019; May 2006). Problematic zones are those areas where a watercourse has a strong connection to groundwater which could thus be degraded (Hörchner et al. 2024). Revitalizations generally have a major impact on the groundwater in the vicinity of watercourses, which can also be caused by the intensification of bank and bottom infiltration (Rozman, Hrkal 2020). A number of studies point to the fundamental influence of the interaction between groundwater and surface water on the river chemistry, biochemical processes (water oxygenation, denitrification, etc.) and the ecological status of the river environment itself (Haase et al. 2013; Kurth, Weber, Schirmer 2015; Magliozzi et al. 2019; Hörchner et al. 2024). In principle,

this interaction is seen as positive, especially in terms of climate change measures which increase the retention capacity of the river floodplain (Magliozzi et al. 2019). Nevertheless, there is a lack of targeted discussion regarding the potential exchange of pollution between surface water and groundwater in the vicinity of the intake area of groundwater for drinking purposes, which in conjunction with an unstable ecosystem can be very problematic to catastrophic.

From this point of view, a major problem is the potential infiltration of pollution into a source of high-quality groundwater within the research area of Cretaceous plateau geological formation, the degradation of which would have an extensive impact on the environment as well as on human society (Illes et al. 2025). The geological structure of the area, characterized by significant fracture permeability, is particularly susceptible to accelerated interaction between surface water and groundwater. This dilemma was considered by the professionals working on the Březová nad Svitavou water source, especially in the 1970s and 1980s during the construction of the 2nd Březová conduit (Viščor 2013). This water source is crucial for hundreds of thousands of inhabitants of Czechia and its protection against pollution has been and should be a priority. From the point of view of protection against pollution, attention was paid in the past to the potential penetration of pollution from the highly polluted Svitava River, which runs through the center of the whole area. For this reason, the five-kilometer-long bed of the river and its tributaries has been made impermeable. The water in the river thus passes through the area without any contact with the surroundings. In recent years, there have been discussions regarding a possible revitalization of this section of the Svitava River since the water quality in the river itself has significantly increased since the 1990s. This paper further addresses aspects of possible revitalization in such a specific area, focusing on the following questions: (1) What risks can be expected when revitalizing a watercourse in the vicinity of a groundwater intake for drinking purposes? And, (2) What form of revitalization would be acceptable with regard to the protection of the intake area? The aim is to identify a suitable method of watercourse revitalization that, on the one hand, supports the development of aquatic ecosystems and, on the other hand, maintains protection against potential groundwater contamination.

2. Research area

The research area (Fig. 1) is located north of Březová nad Svitavou, Pardubice District, Czechia, and constitutes a five-kilometer-long section of the Svitava River, which since the 1970s has had a stone-concrete bottom and trapezium-shaped banks (some parts of this modification date back to 1913). Under the concrete reinforcement there is an impermeable foil and the bottom layer is a clay bed. The

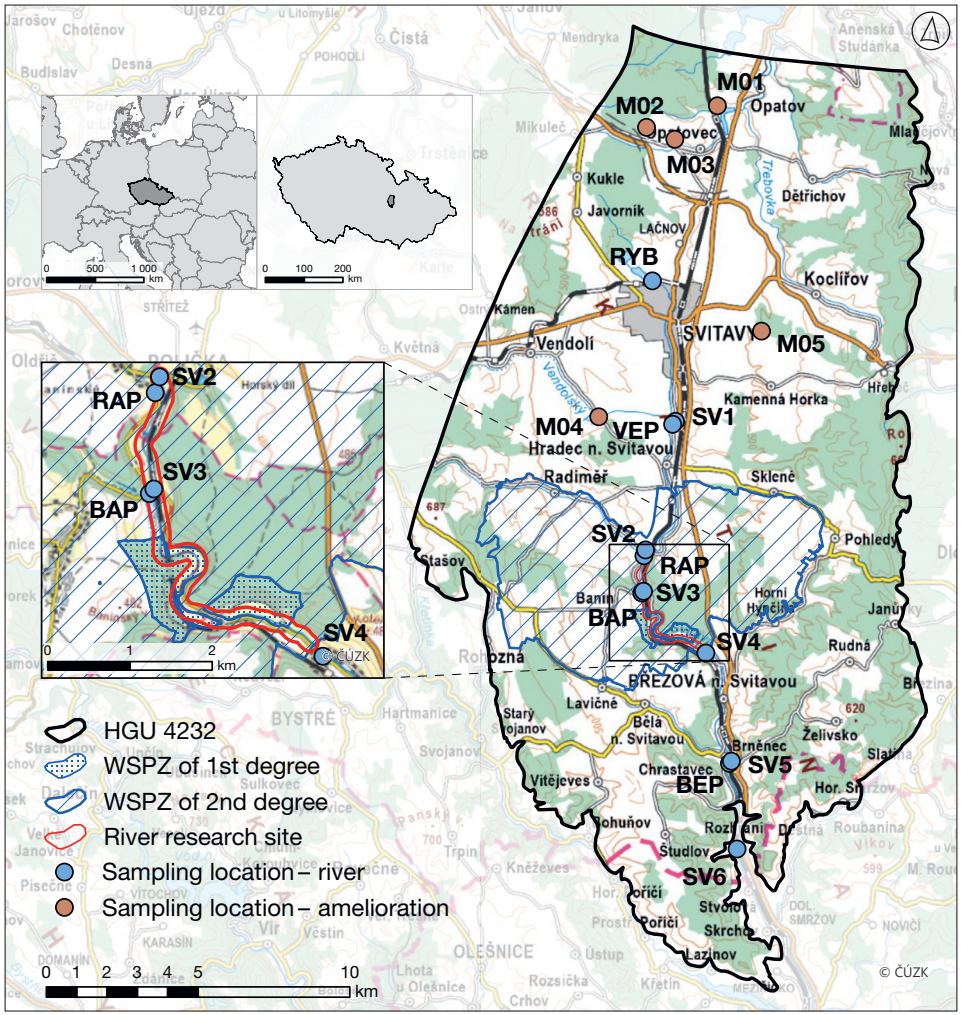


Fig. 1 – Research area and sampling locations

only function of this whole system is to prevent interaction between the surface water and groundwater within the so-called hyporheic zone which in a natural watercourse enables exchange of water between surface water and groundwater surface. This part of the Svitava River passes directly through the water source of groundwater for drinking purposes and therefore it is absolutely undesirable that any degradation of this water should occur.

From the point of view of water source protection, this section is critical for several reasons: (1) The section of the Svitava River passes through a highly urbanized area; (2) above the section there is a large wastewater treatment plant; and

(3) a large part of the Svitava river basin is intensively used for agriculture. In the past, the water in the Svitava River was of a very bad quality, especially due to the intense industrial activities and lack of a wastewater treatment plant in the town of Svitavy. The water quality has significantly improved since then. Nevertheless, concerns about contamination still persist. A sudden temporary deterioration of surface-water quality due to operational failures at the wastewater treatment plant or on major transport infrastructure running parallel to the river cannot be entirely excluded. While the progression of the failure-related pollution in surface water can be monitored and, to some extent, managed, once a contaminant enters the groundwater, its spread is difficult to manage and hard to predict, particularly in the case of deeply buried hydrogeological structures.

The water source in Březová nad Svitavou is formed by two groundwater pumping systems: the 1st and 2nd Březová water supply conduits, pumping water from two hydrogeological collectors, B and C, which are parts of the Hydrogeological unit 4232 Ústecká syncline in the Svitava river basin (HGU 4232; Fig. 1). The whole HGU area is 358 km² and is oriented in a north-south direction representing the eastern edge of the continuous occurrence of Cretaceous sediments in Czechia. The HGU area is formed by alternating permeable hydrogeological collectors (sandstone) and impermeable hydrogeological insulators (claystone; Herčík, Hermann, Valečka 1999; Novotná et al. 2023), which contributes to the formation of a significant source of groundwater used mainly for drinking purposes (Honek et al. 2021; Viščor 2013). The water is supplied via two routes to the city of Brno, about 60 km to the south. This water source is a strategic source for Brno and its agglomeration, comprising over 400,000 inhabitants. Its protection is therefore absolutely crucial.

3. Data and methods

The paper uses data taken from the Czech Hydrometeorological Institute (CHMI; see I.), previous projects handled by the T. G. Masaryk Water Research Institute (WRI; see II.) and measurements performed within the research project, SS06010044 "Defining and evaluating the areas decisive for subsidizing strategic groundwater resources with regard to their protection and stabilization" (Prostředí pro život VI, TA ČR; see III.):

I. Average monthly flows of the Svitava River at the Hradec nad Svitavou and Rozhraní stations between 1985 and 2024: The Hradec nad Svitavou and Rozhraní stations are part of the CHMI measurement network and they record information on flows of the Svitava River on a daily basis. The location of the stations is identical to the offtake point, i.e. SV1 = Hradec nad Svitavou and SV6 = Rozhraní (Fig. 1).

Table 1 – Description of sampling locations of surface water and amelioration on arable land in the research area

Sampling locations of surface water					
ID	Name	River	Discription of location	Coordinates	Number of samples
RYB	Svitavský rybník	Svitava River	infront of pond dam, right river bank	49°45'53.964"N, 16°27'53.054"E	13
SV1	Hradec nad Svitavou	Svitava River	behind the bridge	49°43'27.874"N, 16°28'56.571"E	9
VEP	Hradec nad Svitavou	Vendolský Stream	behind the bridge, behind WWTP	49°43'24.485"N, 16°28'52.487"E	13
RAP	Radiměř	Radiměřský Stream	infront of the bridge	49°41'1.782"N, 16°28'28.878"E	13
SV2	Radiměř	Svitava River	behind the bridge	49°41'7.631"N, 16°28'30.616"E	12
BAP	Banín	Banínský Stream	behind the bridge	49°40'22.168"N, 16°28'32.547"E	11
SV3	Banín	Svitava River	infront of the bridge	49°40'23.969"N, 16°28'34.594"E	13
SV4	Dlouhá	Svitava River	behind the WSPZ of 1st degree	49°39'25.770"N, 16°30'27.434"E	13
BEP	Brněnec	Bělský creak	behind the river confluence	49°37'31.586"N, 16°31'26.142"E	13
SV5	Brněnec	Svitava River	behind the river confluence	49°37'33.674"N, 16°31'28.266"E	13
SV6	Rozhraní	Svitava River	infront of the bridge	49°36'1.499"N, 16°31'53.391"E	13
Sampling locations of amelirotaion					
ID	Name	River	Discription of location	Coordinates	Number of samples
M01	Opatovec	Černý Stream	infront of the pond	49°49'7.107"N, 16°29'8.598"E	1
M02	Opatovec	Mikulečský Stream	infront of the bridge	49°48'36.152"N, 16°27'16.434"E	10
M03	Opatovec	Mikulečský Stream	infront of the pond	49°48'25.123"N, 16°28'7.649"E	10
M04	Vendolí	Vendolský Stream	infront of the culvert	49°43'23.645"N, 16°26'50.131"E	3
M05	Kamenná Horka	*nameless stream*	infront of the pond	49°45'14.039"N, 16°31'0.819"E	8

II. Results of macrozoobenthos monitoring: The saprobic index of macrozoobenthos was used between 1970 and 2010 for the evaluation of water quality in rivers in Czechia. The index indicates the relationship of the invertebrates living in bottom sediments to the indicators of organic pollution and to the extent of decomposition processes (Hegrab, Khalifa 2021). The index was monitored during five-year cycles within a special monitoring network (ČSN 1998; Zahrádková et al. 2015). In the paper, results from 1985, 1995 and 2005 are presented to compare the pollution development over time.
III. Sampling in 16 selected locations within the HGU area (Fig. 1; Table 1): Surface-water sampling was carried out from June 2023 to June 2024; amelioration water sampling took place from April 2024 to March 2025. This dataset has not yet been publicly published in such a comprehensive form, and it is further discussed in more detail in this paper.

Additionally, map outputs were created on the basis of data sets provided by the Czech Office for Surveying, Mapping and Cadastre (COSMC) – Basic topographic map of CR 1: 10,000. GIS analyses and map outputs were processed in the ArcGIS Pro 3.4.2 software of the company ESRI™.

4. Results

Figure 2 shows the annual course of average monthly flow in the Svitava River in the stations of Hradec nad Svitavou and Rozhraní over a ten-year period (the grey base area shows the long-term monthly average for the period between 1985 and 2024). The Svitava River in both profiles is characterized by increased water flow in spring months, especially in March. This can be attributed to snow melt, spring rains and agricultural land without vegetation when surface runoff is easier. This spring peak is typical for almost all selected watercourses although sometimes it occurs later in the following spring months. Another significant peak appears in July, due to the more frequent occurrence of intense precipitation events (e.g. the 1997 floods in Moravia). It is particularly in this month that the most significant change compared to the long-term average can be seen. Other seasons of the year, the end of summer and autumn, have always been periods of the lowest flows and the years monitored have almost always been under the long-term average.

From the long-term perspective, the Svitava River flow has been decreasing, except for years with above-average rainfall. In warm months, the watercourse often completely dries up, which was observed at the Hradec nad Svitavou station. A slightly different situation can be noticed further downstream where the steadier flow in the river has been influenced by the runoff from the Hradec nad Svitavou WWTP (large municipal WWTP for the town of Svitavy) and also by

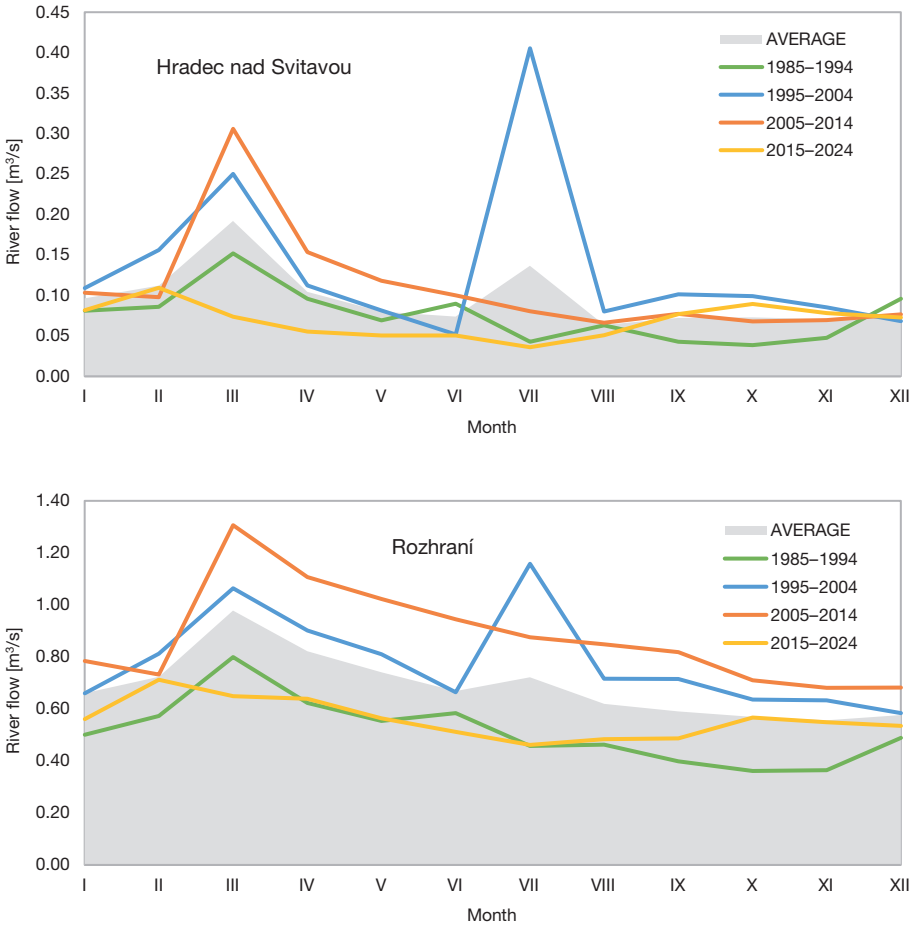


Fig. 2 – Long-term average monthly flow [m³/s] of the Svitava River at the Hradec nad Svitavou and Rozhraní stations (stations operated by the CHMI) during the time period from 1985 to 2024

several smaller tributaries, thanks to which the watercourse at the Rozhraní station does not dry up completely.

Pollution in the Svitava River was caused in the past mainly by the concentration of the textile industry around the river and by the discharge of wastewater from all settlements in the vicinity of the river. The zoobenthos saprobability index evaluation results demonstrate a gradual improvement in the river water quality between 1985 and 2005 (Fig. 3). The original very bad quality was caused mainly by the wastewater from the town of Svitavy and intense agricultural activity in the spring area of the Svitava River. In this section the river does not contain enough water to water down the pollution, in contrast to the case further downstream. Intense pollution spread to the water source area in Březová nad Svitavou and for

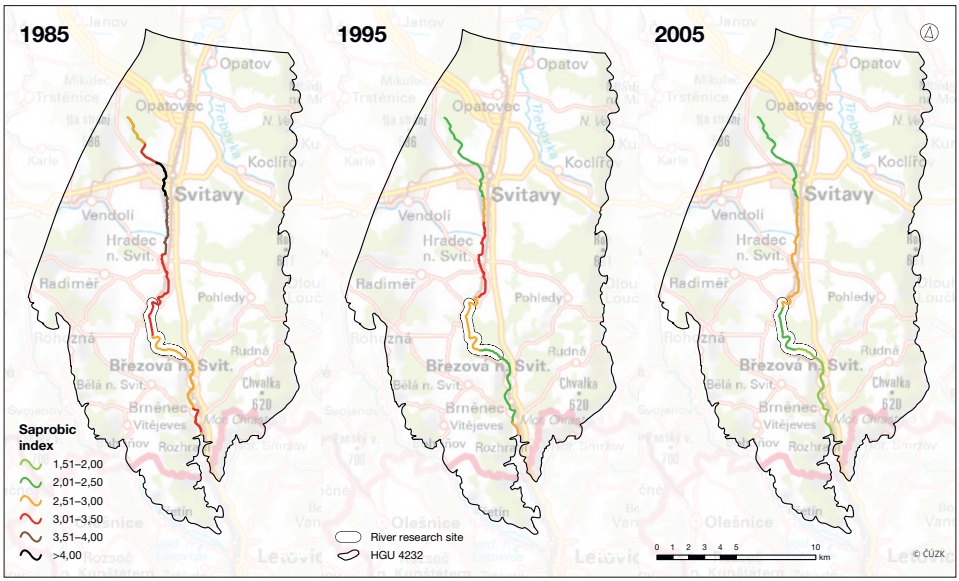


Fig. 3 – Development of the zoobenthos saprobability index in the Svitava River (upper part of the river) from 1985 to 2005

this reason, the river bed was modified in the 1970s to prevent pollution infiltration into the groundwater.

The river water quality has been gradually improved (Fig. 3), mainly due to a decline in industrial activity and the diversion of most wastewater to the Hradec nad Svitavou municipal WWTP. Nevertheless, the area between the town of Svitavy and the research location (the beginning of the reinforced part of the river) remains in a worse condition due to the pollution washed away from settlements and roads. A potential risk is posed by the Hradec nad Svitavou WWTP itself where the treated water is discharged directly into the watercourse. A low flow in the Svitava River often prevents the substances in the treated water from being naturally diluted and eliminated.

Long-term situational monitoring is carried out in the territorial scope, which is not sufficient for the evaluation of the current state of the area of interest. Therefore, annual monitoring of surface water and outlet points of amelioration outfalls was selected between 2024–2025 in the network of locations according to the study requirements. Examination results are part of the standard agenda of the laboratory. In the following text, only those indicators that are relevant to the objectives of the study are presented. In Table 2 these selected indicators are processed as average values taken usually from 12 measurements. A lower number of measurements in some locations is due to low to zero flows at certain times of

the year. Table 1 therefore also includes the number of relevant sampling events from which the average values were calculated.

The visualization in Figure 4 was created to provide a better understanding of the location, type and severity of water pollution. Quality indicators are divided into five groups according to their characteristics:

- Oxygen regime: O_2, BOC5, CHOC-Mn
- Microbiology: Fecal coliform bacteria, Escherichia coli, Enterococci
- Salts: RL, RAS, CL, SO_4, Mg, Ca
- Nutrients: nitrate regime, o-PO_4 total, TOC
- Metals: Al, As, Cd, Cr, Cu, Fe, Hg, Ni, Ps, Zn.

Each group was evaluated for the given location according to the worst evaluated indicator. A four-color scale ranging from the best (blue) to the worst (red) quality was used to express the quality status. Each monitored location has a sign on the map with five sections colored according to the monitoring results. Figure 4 clearly shows that, taking into account all groups of indicators, the locations with the worst quality are the ones under the town of Svitavy (SV1) and under the Svitavy wastewater treatment plant on the Vendolský Stream (VEP). With the exception of the presence of metals, this unfavorable condition persists in other locations on the Svitava River above the intake area (SV2 and SV3). A reduced number of metals in the water of this section may be caused by their entrapment in the river bottom sediments, which are created here due to low flows and low hydraulic head.

The favorable nutrient status of all monitored drainage waters (M01–05) is surprising although a worse status was expected due to nitrate leakage from the arable land (Fig. 4). However, it appears that any excess nitrate in the flat upland part of the river basin is directly transferred to groundwater. Unfavorable evaluation of this nutrient group in other locations is mainly due to phosphorus leakage from municipal and possibly industrial pollution sources.

The best water quality was in the location M01 (Fig. 4). According to available resources, this is a drainage water outlet under a large swathe of arable land. The laboratory results, however, suggest that this is a groundwater spring that has been diverted by a drainage pipe further below to facilitate the cultivation of the entire agricultural land.

For some significant indicators the data have been processed in more detail – Figure 5 to Figure 10. All sampling was carried out at times of average or lower flows; no situation was captured after a heavy rainfall or during a prolonged period of elevated water levels. The variability of pollutant concentrations is thus most likely due to the seasonality of agricultural work or fluctuations in the efficiency of the treatment processes at the WWTP that discharges into the Svitava River. In the case of heavy rainfall, increased concentration of pollution from diffuse agricultural sources can be expected, together with erosion-driven

Table 2 – Average result values of chosen parameters of surface water

Sampling location	Fec. colif. bact.	Escherichia coli	Enterococci	pH	El. conduct.	BOC5	CHOC-Mn	Cl	SO4	Amonn. ions
ID	KTJ/100 ml	KTJ/100 ml	KTJ/100 ml	—	mS/m	mg/l	mg/l	mg/l	mg/l	mg/l
RYB	3,280.00	33.17	232.17	7.82	38.80	6.01	8.44	26.10	34.13	0.29
SV1	184,000.00	10,205.00	7,077.78	7.55	57.82	3.20	5.41	57.60	47.50	0.59
VEP	328,300.00	187,641.67	45,046.92	7.38	76.88	2.96	6.85	74.18	80.68	1.90
RAP	5,900.00	1,289.23	2,472.31	7.69	40.58	2.19	3.51	8.73	33.72	0.10
SV2	87,000.00	19,244.00	6,856.67	7.61	68.23	2.30	5.77	65.82	70.68	0.69
BAP	1,800.00	2,380.00	9,928.18	7.76	70.07	3.55	3.87	25.12	67.15	0.65
SV3	84,000.00	9,572.31	5,210.77	8.00	59.29	1.71	4.00	46.28	55.79	0.64
SV4	32,800.00	2,353.25	2,143.08	7.54	60.68	1.39	2.67	34.19	50.63	0.24
BEP	1,600.00	968.46	991.08	7.62	52.27	2.47	2.25	25.76	44.02	0.05
SV5	30,400.00	2,110.83	2,044.62	7.58	57.14	0.99	1.84	28.92	46.72	0.15
SV6	63,000.00	3,158.33	3,061.54	7.65	55.54	0.98	2.55	29.71	47.82	0.25
M01	—	—	—	7.40	39.10	40.20	3.01	6.57	48.60	0.02
M02	1.00	63.50	98.13	7.52	16.38	18.42	10.03	3.97	26.17	0.03
M03	12.00	168.56	153.67	7.19	36.72	38.48	6.51	6.10	40.68	0.04
M04	—	4,869.67	3,174.67	7.08	37.57	39.30	6.37	11.71	31.97	0.06
M05	20.00	333.33	259.50	7.57	22.61	24.20	33.1	9.08	33.13	0.02
Sampling location	NO_3	NO_2	o-PO4 total	NL 105	RL105	Na	K	Ca	Mg	Al
ID	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l
RYB	5.50	0.06	0.23	28.05	267.15	12.46	4.22	59.10	3.78	174.94
SV1	14.11	0.25	0.36	28.58	375.33	32.02	3.11	75.77	3.48	279.01
VEP	46.90	0.47	2.47	33.87	518.31	53.12	13.82	83.95	5.91	270.68
RAP	24.08	0.10	0.30	29.82	285.46	2.45	2.35	76.61	1.71	267.00
SV2	25.65	0.51	1.33	15.82	442.17	42.84	10.21	79.03	4.88	245.01
BAP	48.76	0.81	1.74	22.96	507.36	12.52	7.20	122.59	2.46	444.03

SV3	26.81	0.25	0.86	15.34	401.77	25.16	6.31	83.76	3.64	213.38
SV4	35.90	0.13	0.47	14.25	435.23	15.50	3.86	98.62	3.27	313.73
BEP	40.28	0.11	0.31	25.90	401.00	6.23	2.32	92.89	2.51	225.09
SV5	31.08	0.09	0.34	13.71	407.38	10.82	3.10	95.62	3.43	391.03
SV6	31.28	0.09	0.43	19.78	401.77	11.08	3.13	95.94	3.45	394.94
M01	11.20	< 0.03	< 0.03	< 2	271.00	4.43	< 1	64.30	4.25	-
M02	7.70	0.05	0.09	6.18	133.44	3.64	2.05	24.88	2.19	323.29
M03	17.31	0.05	0.09	3.80	295.22	4.90	1.83	69.14	5.84	307.95
M04	6.27	< 0.03	0.23	18.00	270.00	3.25	1.95	66.70	3.32	1,019.50
M05	39.02	0.13	0.13	16.84	183.14	3.15	1.82	29.41	3.38	81.10

Sampling location	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
ID	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
RYB	4.39	< 0.1	< 1	14.77	624.00	< 0.05	65.36	4.05	2.11	8.00
SV1	2.46	0.10	1.33	4.20	581.22	< 0.05	56.00	3.25	2.53	28.33
VEP	1.83	< 0.1	3.34	5.79	558.54	0.06	63.75	2.77	1.98	27.10
RAP	1.37	< 0.1	1.85	3.56	225.67	< 0.05	46.33	2.14	2.22	28.00
SV2	1.74	< 0.1	1.42	3.38	323.67	< 0.05	48.63	2.46	1.84	19.20
BAP	1.94	< 0.1	1.34	6.55	328.00	< 0.05	30.17	3.35	2.39	18.67
SV3	1.62	< 0.1	1.27	3.50	235.83	< 0.05	43.00	3.01	2.20	35.00
SV4	1.80	< 0.1	1.40	2.99	255.81	< 0.05	39.50	2.49	2.47	26.50
BEP	1.38	< 0.1	< 1	4.49	162.00	< 0.05	38.25	7.41	1.87	15.00
SV5	1.80	< 0.1	1.19	4.10	173.90	< 0.05	33.50	2.67	2.07	23.50
SV6	1.33	0.13	2.33	5.00	324.67	< 0.05	45.00	3.66	3.52	31.00
M01	—	—	—	—	34.00	< 0.05	< 20	—	—	< 5
M02	2.30	0.17	1.56	2.72	331.78	< 0.05	48.80	4.22	1.03	< 5
M03	1.97	0.12	1.53	3.81	245.89	< 0.05	47.20	3.17	< 1	< 5
M04	2.23	< 0.1	1.20	3.29	1355.00	< 0.05	49.00	5.55	3.90	< 5
M05	1.77	< 0.1	1.47	2.00	377.67	< 0.05	38.00	2.07	< 1	< 5

"—" marker means that the value could not be determined due to a small number of samples or was not determined at all

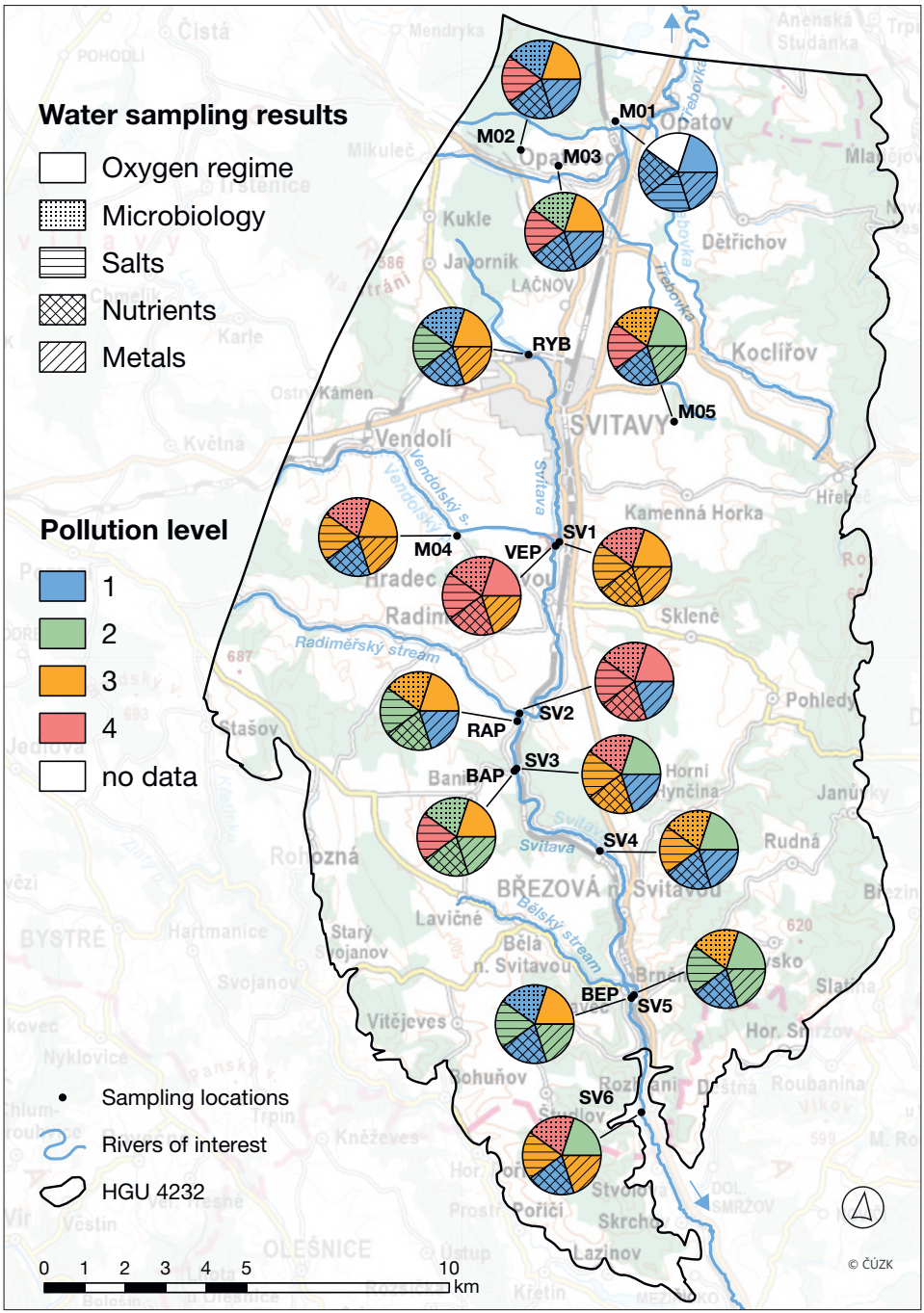


Fig. 4 – Water sampling results throughout the HGU 4232 research area.

Figures 5–10 show the results of the basic statistical analysis of the selected parameters in each sampling location, with the thin lines showing the variance of values (MIN and MAX), the lower box boundary the 1st quartile value, the upper box boundary the 3rd quartile value, and the interface between the light and dark blue boxes the median value.

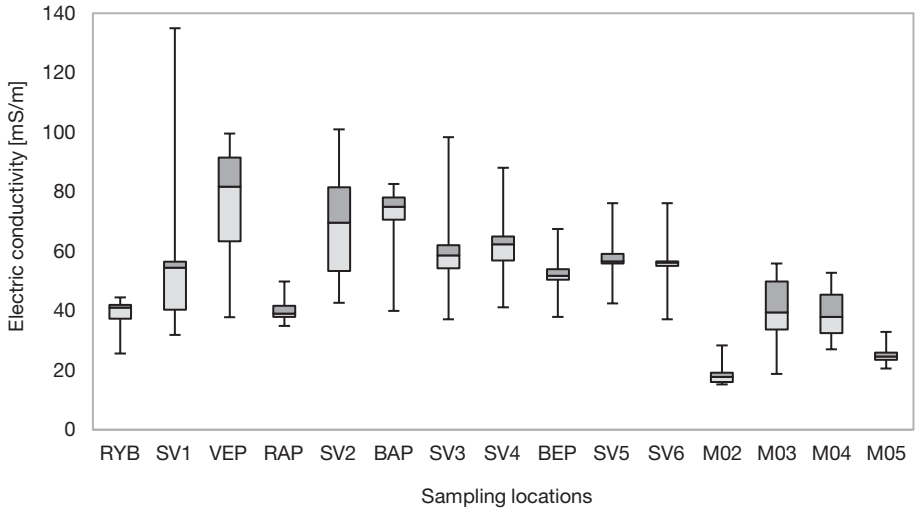


Fig. 5 – Variance of values of electric conductivity [mS/m] during the time period from June 2023 to March 2025

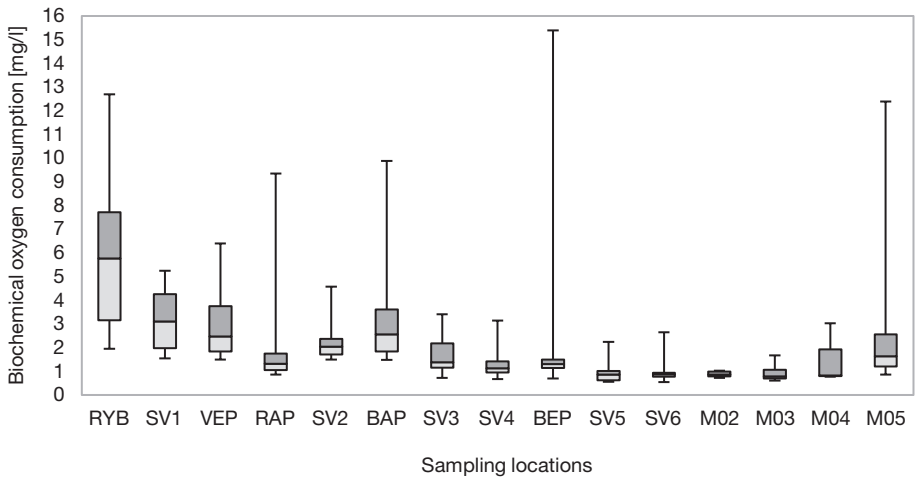


Fig. 6 – Variance of values of biochemical oxygen consumption [mg/l] during the time period from June 2023 to March 2025

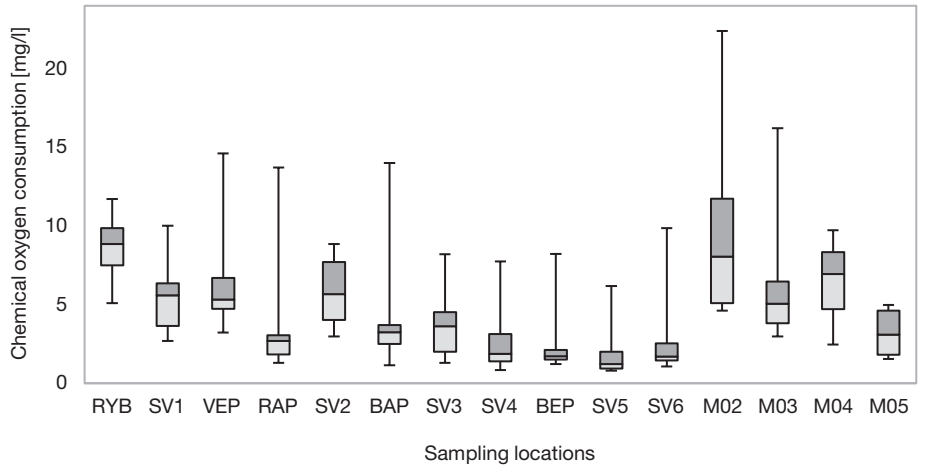


Fig. 7 – Variance of values of chemical oxygen consumption [mg/l] during the time period from June 2023 to March 2025

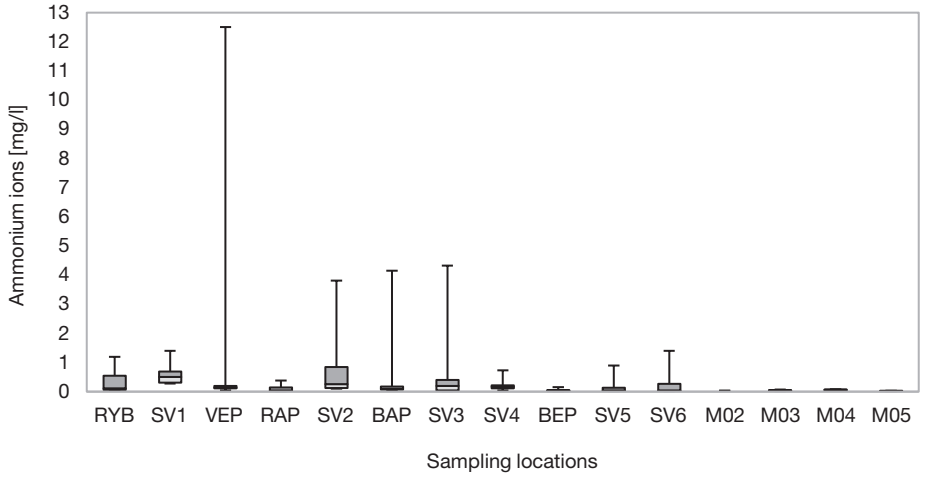


Fig. 8 – Variance of values of ammonium ions [mg/l] during the time period from June 2023 to March 2025

wash-off of topsoil; whereas for pollutants originating from municipal and industrial point sources, the pollution will more likely be diluted, resulting in reduced concentration in surface water. In particular, the left-bank part of the Svitava river basin, upstream of Březová, is highly susceptible to erosion. Based on previous experience, the majority of concentrated flow paths and their surrounding areas have already been grassed over or equipped with additional erosion-control measures.

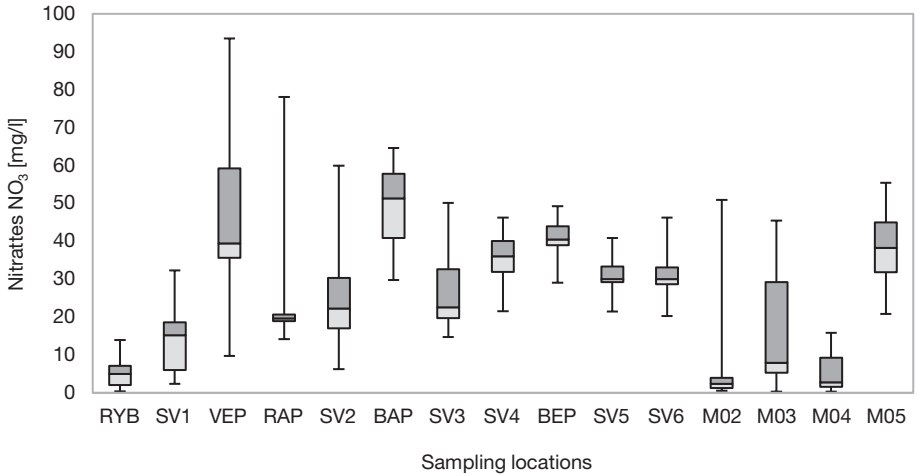


Fig. 9 – Variance of values of nitrates (NO_3) [mg/l] during the time period from June 2023 to March 2025

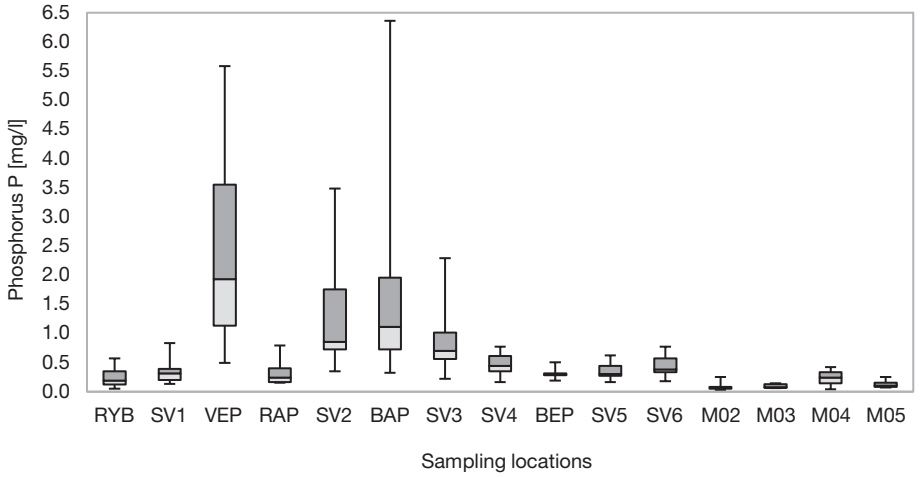


Fig. 10 – Variance of values of phosphorus (P) [mg/l] during the time period from June 2023 to March 2025

5. Discussion

The positive benefits of watercourse revitalization are, generally speaking, indisputable and have been confirmed many times in the context of stabilizing aquatic ecosystems (Shackelford et al. 2013; Durčák et al. 2017), supporting water retention in the landscape and mitigating the impacts of climate change (Edwards et al. 2012; Beran 2022) and serving as part of anti-flood measures (Rozman,

Hrkal 2020). In 2000, Directive 2000/60/EC of the European Parliament and of the Council (EU 2000) – Water Framework Directive – was adopted, which enabled national legislation and related practical measures to be adopted by EU countries for the overall improvement of the aquatic environment. The Directive was focused mainly on surface waters; groundwaters are mentioned only marginally in the context of relevant topics.

Biologists played an important role in the creation of the Directive (EU 2000) and therefore priority was given to addressing the problems of aquatic communities and water-dependent animals and plants. The Directive assumed that by 2027 all waters would be in their natural state and if this was not so, everything possible would be done to maximize the ecological potential. During the implementation of the Directive, important reasons, relevant for maintaining the existing status of the watercourse with its required structures, have been highlighted, such as flood protection measures, accumulation of surface water for drinking purposes or modification of the watercourse leveling for the use of hydraulic power. These reasons do not yet include a case where it is appropriate to maintain a watercourse section unrevitalized in order to protect another water body, such as groundwater. The Directive (EU 2000) and other regulations aim at returning rivers to their natural states. Revitalizations are proposed even in places where the technical adaptations have been going on for more than 100 years and during that time qualitative relationships have already been established in the hydraulic environment and throughout the whole landscape (Kurth, Weber, Schirmer 2015; Richter 2023). In such cases, revitalization measures need to be carefully considered to avoid other damage (Bridhikitti et al. 2021; Hörchner et al. 2024).

Proposals for the revitalization of the Svitava River and its tributaries have been discussed and smaller local studies have also been carried out (e.g. IEVA 2022). However, some studies' results indicate that a full-scale revitalization in the immediate vicinity of a water source is unlikely to be possible here due to its assumed impact on the quality of groundwater. The results presented here also evidence this assumption as they point to the pollution of the Svitava River caused by the local waters and runoff from the surrounding watercourses. Great variability in results (see Attachments S2 to S6) indicates the risk of sudden high to emergency pollution levels. In the case of the Banínský Stream, a right-side tributary of the Svitava River, its alluvial plain has already been revitalized (PMO 2024). The results of the collected water analysis, carried out by the water source operator, demonstrate a subsequent deterioration of microbiological indicators in the collected water although a direct link to the revitalization has yet to be assessed.

Maintaining the impermeability of the river bottom while revitalizing other elements, which will not conflict with this requirement, could be a compromise solution of revitalization in these complex cases. Figure 11 is an example of

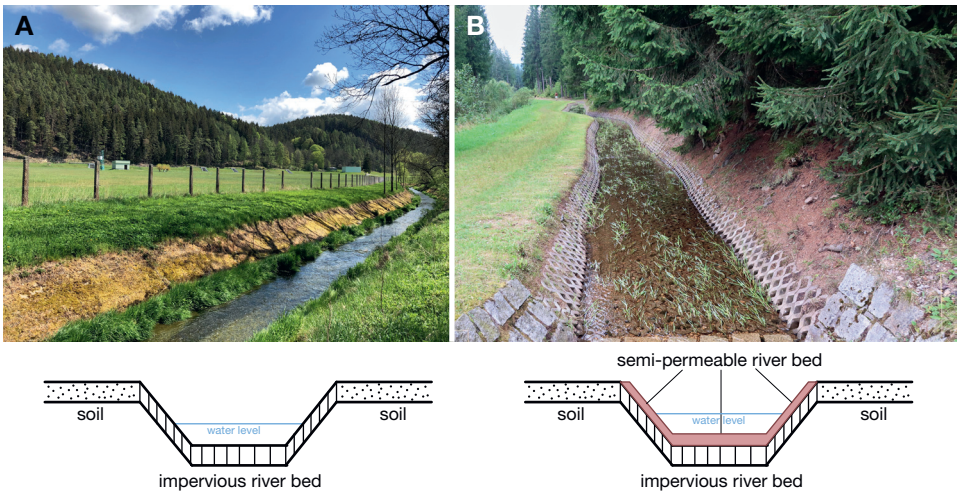


Fig. 11 – (A) River Svitava in Březová nad Svitavou (CZE; Photo by D. Honek, 12. 9. 2018); (B) the Hanggraben near Wildenthal (GER; Photo by M. Dzuráková, 20. 8. 2024). The impervious river bed is made (from the base) of a layer of clay, an impermeable foil, and a stone-concrete layer.

a possible modification of the water trough where the impermeable layer in the existing composition of the cross section (Figure 11A) is covered by concrete lattice which trap sediments and enable hydraulic ecosystem development. The proposed possible suitable solution was inspired by the revitalization in Hanggraben near Wildenthal in Germany (Figure 11B), where this kind of modification of a part of an artificial channel helped transfer water to a water tank. Based on the enhancement of riverine and ecosystem processes, no increase in maintenance demands is anticipated for the watercourse modified in this manner. Natural fluctuations in flow will lead to the trapping of an adequate amount of sediments and its revitalization; whereas the transport capacity of higher flows will remove excess sediments. Under significantly low to zero flows, moist sediment will provide conditions suitable for the survival of organisms that would not survive in a paved, smooth, and dried-out trough. This technical solution could also enable the transfer of problematic wastewater, e.g. water from a wastewater treatment plant or occasional accidental contamination, through the drinking water intake area.

If such a modified revitalization of the Svitava River is partially designed and implemented, it is advisable to use the variant with the impermeable bottom also upstream up to the confluence of the Vendolský Stream, the recipient of the treated municipal wastewater from the town of Svitavy, given the unstable water quality. In connection with landscape modifications in the watercourse surroundings, it would be possible to create a functional ecosystem, providing valuable services both to nature and human society (Gumiero, Boz 2017; Magliozzi et al. 2019).

6. Conclusion

This paper investigates the benefits and risks of the revitalization of the Svitava River and its tributaries in respect to it being an important underground source of drinking water. It presents general, theoretical as well as practical approaches to revitalization of watercourses under different conditions, including various authors' ideas and experience. However, during the research no example has been found which would correspond to the specific situation in the monitored location HGU 4232 Ústecká syncline in the Svitava river basin. The example of HGU serves as a basis for discussion over negative anthropogenic consequences connected with intense agriculture, industry and settlements and their impact on groundwater quality via interactions with surface water.

Quality indicators of surface and drainage waters have been analyzed over the course of two years to monitor the current state. The data obtained and subsequent discussion have confirmed that under the given conditions, a full-scope revitalization is not suitable because it could pose a risk to the watercourse quality. It seems to be indispensable to maintain technical measures for the impermeability of the river bed in selected parts of watercourses affected by pollution. In spite of that, it does not mean the revitalization should be completely given up. The paper discusses revitalization options which enable all other benefits except for the contact between the surface water and groundwater, which is entirely unacceptable in locations of this type. The modified revitalization will bring benefits to life in watercourses and their immediate surroundings and will enhance the overall character of the landscape. Economic evaluation, i.e. financial demands of the proposed solution, was not part of the research project. However, given that the Svitava River trough will need to be repaired in that section in the near future due to its current unsatisfactory condition, the situation represents a comparison of two different solution variants. No significant difference in investment costs is anticipated, as would be the case if a zero variant (leaving it in the current state without any intervention) was compared with any type of new modification. If this solution is accepted, further discussion with biologists, landscape ecologists etc. will be required to consider what elements and their parameters should be chosen.

In artificial troughs, aquatic vegetation appears spontaneously due to the wear and tear of the trough reinforcement. Nevertheless, the proposed modification of the watercourse revitalization could support the development of the aquatic ecosystem to a much greater extent, even when the original purpose of the trough reinforcement is maintained. The solution itself is relatively easy and able to be applied and adapted for similar locations. The technical solution is based on a real implementation, albeit with a different objective. This offers an opportunity to continue and develop this technical solution and to link it to other measures in the landscape, particularly in the unpolluted parts of the river basin, to maintain and enhance groundwater production.

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Horizontal and vertical dimensions of pedestrian accessibility to public transport stops in Liberec and Zlín

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ABSTRACT This study examines pedestrian accessibility to public transport stops through a two-dimensional framework integrating horizontal (network-based walking distance) and vertical (elevation difference) components. The analysis deliberately isolates the walking access stage and does not assess service frequency, travel time, or network performance. The framework is applied to Liberec and Zlín, two medium-sized Czech cities with hilly terrain and contrasting urban structures. For built-up areas, network walking distances and elevation differences to the nearest stop were calculated and combined into a synthetic horizontal–vertical accessibility typology. Results show that both cities have generally favourable proximity to stops, but terrain substantially modifies accessibility patterns, especially in Liberec. The combined framework identifies short-but-steep and far-but-flat areas that remain hidden when distance and elevation are evaluated separately. The study offers a transparent, transferable approach for assessing pedestrian stop accessibility in topographically complex urban environments and provides a spatially explicit basis for further accessibility analysis.

KEY WORDS pedestrian accessibility – public transport stops – network distance – elevation difference – terrain

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1. Introduction

Accessibility is a central concept in transport geography and urban studies, commonly used to assess how effectively transport systems connect people to activities, services, and opportunities. In the context of public transport, accessibility is most often evaluated through indicators related to service performance, such as frequency, travel time, or network connectivity. While these approaches provide important insights into system efficiency, they tend to overlook a more fundamental layer of everyday mobility: the physical effort required to reach public transport infrastructure on foot.

Pedestrian access to public transport stops constitutes a necessary precondition for any subsequent use of public transport services. Even in cities with dense networks and frequent services, unfavourable walking conditions may limit the practical usability of public transport, particularly for populations with reduced mobility or in environments shaped by complex urban morphology and terrain. Despite this, pedestrian stop accessibility is frequently treated as a secondary or implicit component of broader accessibility assessments, rather than as an analytical dimension in its own right.

A growing body of research has highlighted the conceptual ambiguity surrounding the term "public transport accessibility", which is used to describe analytically distinct phenomena ranging from spatial proximity to infrastructure to service quality and social inclusion. This diversity reflects the coexistence of time-based usability simulations, service-oriented evaluations, and normative perspectives concerned with transport disadvantage and transport justice (Bernard 2022, Lucas 2012, Martens 2016). Without clear conceptual separation, these perspectives risk being conflated, complicating interpretation and limiting comparability across studies. In response, this paper adopts a deliberately narrow and explicit focus on pedestrian accessibility to public transport stops, defined as the conditions under which individuals can reach the nearest stop on foot. The term pedestrian accessibility is used throughout the paper to distinguish walking access to stops from barrier-free accessibility, which refers to infrastructure-related or user-specific constraints such as platform design, boarding conditions, or reduced mobility.

Pedestrian accessibility is shaped by multiple spatial factors, of which horizontal distance and terrain-related effort are particularly important. Network-based walking distance captures the spatial configuration of streets and paths, while elevation differences influence walking effort and comfort, especially in hilly urban environments. Analysing these dimensions separately, however, may obscure locations where physical constraints accumulate. Their combined assessment therefore offers a more comprehensive understanding of pedestrian access conditions than one-dimensional distance-based approaches.

Medium-sized cities provide a particularly relevant context for examining pedestrian stop accessibility. Compared to large metropolitan areas, they often exhibit lower redundancy in public transport networks, greater sensitivity to urban form, and a stronger influence of local topography on everyday mobility. In Central Europe, many such cities are characterised by hilly terrain, historically layered urban structures, and compact but spatially heterogeneous development patterns. In such contexts, terrain represents a structural constraint for urban mobility systems, influencing public transport network design and operation in hilly cities (Papa, Santo Zarnik, Vukašinović 2022). These characteristics make them suitable case studies for investigating how distance and terrain related constraints interact in shaping pedestrian accessibility. At this spatial scale, lower network redundancy and stronger sensitivity to urban form make stop accessibility particularly dependent on spatial configuration and local conditions (Korczyński 2019).

This study applies a two-dimensional analytical framework integrating horizontal and vertical components of pedestrian accessibility to two medium-sized Czech cities with hilly terrain: Liberec and Zlín. A key advantage of the proposed approach is that it relies exclusively on publicly available spatial data, enabling transparent, reproducible, and easily transferable analyses without the need for proprietary datasets. This lowers barriers to comparative research and facilitates application in diverse urban contexts.

The paper addresses the following research questions:

1. How do horizontal and vertical dimensions of pedestrian accessibility to public transport stops differ between Liberec and Zlín?
2. To what extent does terrain influence spatial patterns of pedestrian stop accessibility within built-up areas?
3. Does the combined assessment of horizontal and vertical accessibility reveal areas of cumulative physical constraints that remain hidden in one-dimensional analyses?
4. To what extent is the proposed analytical framework transferable to other medium-sized cities with complex terrain?

By explicitly separating and recombining horizontal and vertical dimensions of pedestrian accessibility, the study aims to contribute both empirically and methodologically to ongoing debates on accessibility measurement in transport geography.

2. Approaches to public transport accessibility and performance

When evaluating spatial units in terms of public transport provision, accessibility represents one of the most widely applied analytical concepts. Existing research

labelled as public transport accessibility, however, encompasses a broad spectrum of approaches ranging from infrastructure proximity and spatial coverage to service performance, temporal availability, and system efficiency. Accessibility-based evaluations therefore provide an effective framework for examining the spatial distribution of transport infrastructure and services, as well as their relationship to population distribution and urban form, but they also differ substantially in their analytical focus and underlying assumptions.

One of the most frequently used data standards in public transport research is the General Transit Feed Specification (GTFS), which enables the standardised representation of public transport schedules and spatial information on stops, routes, and trips (GTFS 2024). The static GTFS feed consists of mandatory files describing agencies, stops, routes, trips, stop times, and service calendars, complemented by optional files addressing transfers, fares, or service exceptions. GTFS datasets are typically published by transport operators and are increasingly available as open data. In combination with other spatial datasets – such as OpenStreetMap, census data, and national geodatabases – GTFS provides a robust basis for analysing public transport accessibility and efficiency in urban and regional settings.

GTFS-based analyses have been applied across a wide range of thematic contexts. Farber, Morang, Widener (2014) used GTFS data to model the temporal variability of transit-based accessibility to essential services, while Tao, Rohde, Corcoran (2014) examined the impacts of newly introduced transport services. Luo et al. (2019) focused on travel cost and impedance modelling, and Andrei, Luca (2021) analysed operational efficiency during peak periods. Interactive visualisation tools and decision-support systems based on GTFS data have also been developed, including PubtraVis (Prommaharaj et al. 2020).

An alternative to GTFS consists of timetable datasets published directly by individual transport operators. These datasets, however, often lack standardisation and interoperability, which complicates their direct analytical use. In such cases, web scraping and data transformation techniques may be employed to convert heterogeneous timetable formats into structured datasets suitable for spatial analysis.

From a methodological perspective, research on public transport accessibility and efficiency can be grouped into several broad thematic areas according to the primary analytical focus and the parameters under consideration. Beyond distance-based accessibility, public transport systems have also been examined using complex network analysis to capture structural properties such as connectivity and node importance (Háznagy et al. 2015).

The first thematic area addresses infrastructure-based and spatial accessibility. Studies in this category typically evaluate walking distance to public transport stops, the configuration of street networks, and the spatial relationship between population distribution and transport infrastructure. A frequently applied approach in this context is the Public Transport Accessibility Level (PTAL)

method, which combines proximity to stops with service frequency and network connectivity. Although PTAL extends beyond pure pedestrian stop accessibility by incorporating service frequency and network characteristics, it illustrates how proximity to stops is typically embedded within broader composite indices highlighting the need to analytically isolate the pedestrian access component. Tiran, Mladenović, Koblar (2015) applied PTAL to assess public transport accessibility in Ljubljana, while Alamri et al. (2023) evaluated transport networks, service periodicity, and street typologies by transport mode. Kaszczyszyn, Sypion-Dutkowska (2019) analysed the proportion of street length within different accessibility intervals. These studies increasingly rely on GIS-based spatial indicators derived from openly available data to evaluate stop coverage, network configuration, and the spatial adequacy of public transport provision (Alamri et al. 2023; Andrei, Luca 2021; Roşu, Blageanu 2015). In Central Europe, Puławska, Wiesław (2011), and Puławska (2014) examined infrastructure accessibility in relation to service quality and tariff conditions.

Related approaches assess ideal and actual stop accessibility using buffer-based coverage indices and distance thresholds (Foda, Osman 2010). These methods provide a straightforward representation of spatial coverage but often neglect network configuration and terrain-related constraints.

A growing body of research emphasises the importance of terrain and hypsometric conditions in shaping public transport accessibility. Elevation differences and slope affect the physical effort required to reach public transport stops and influence walking propensity, particularly in hilly urban environments. Djurhuus et al. (2014), Kaszczyszyn, Sypion-Dutkowska (2019), and Nandan et al. (2022) demonstrate that uneven terrain can significantly reduce effective accessibility even in areas with dense stop coverage. Rissel et al. (2012) highlight that increased walking effort associated with uphill gradients may limit the ability of public transport users to meet physical activity recommendations. Empirical evidence further suggests that walking to stops in hilly areas may discourage public transport use altogether (El-Geneidy et al. 2013, Su et al. 2023).

Integrating hypsometric analysis into accessibility studies enables a more nuanced understanding of spatial barriers. Ford et al. (2015) and Su et al. (2023) demonstrate that combining walking distance with elevation change provides a more realistic representation of access conditions than distance-based indicators alone. GIS-based analyses further support the identification of spatial disparities by mapping elevation-related constraints in relation to public transport networks (Hino et al. 2013).

Another strand of research focuses on user perception and perceived accessibility, recognising that objective measures do not fully capture how individuals experience access to public transport. Lättman, Friman, Olsson (2016) show that perceived accessibility is often lower in areas characterised by poor pedestrian

permeability and pronounced elevation differences. Survey-based approaches incorporating subjective evaluations of walking effort and comfort have been used to complement spatial analyses (Djurhuus et al. 2014).

The second thematic area addresses temporal accessibility and service frequency. Studies in this category examine travel time, waiting time, and service periodicity, often with a focus on peak periods. Goliszek, Połom (2016) combined accessibility measures with service frequency. Goch et al. (2018) examined the temporal accessibility of Warsaw's city centre. Comparative analyses of public and private transport performance across different times of day were conducted by Goliszek (2019, 2021). In the Czech context, Fitzová, Matulová, Tomeš (2018) and Fitzová, Matulová (2020) evaluated temporal accessibility alongside transport efficiency indicators. Chowdhury, Ceder, Velty (2014) combined quantitative and qualitative indicators, including transfer smoothness and information availability. Such approaches demonstrate that accessibility patterns vary substantially over time, whether assessed through large-scale national monitoring frameworks or through analyses of daily mobility rhythms captured by timetable and intelligent transport system data (Horák et al. 2014; Mulíček, Osman, Seidenglanz 2015; Kraft, Blažek, Marada 2022).

The third thematic area encompasses synthetic efficiency indices and comprehensive evaluations typically aggregating spatial coverage, service intensity, and network characteristics into a single compensatory score, often combining GTFS data with population statistics or gravity and centrality-based formulations (Sha Al Mamun, Lownes 2011; Kaeoruean et al. 2020; Yang et al. 2019). Differences between supply and demand have been examined using composite indicators by Kaeoruean et al. (2020) and Żochowska et al. (2022). Roşu, Blageanu (2015) developed a composite stop efficiency index incorporating functionality, utilisation, connectivity, and population catchment. Korczyński (2019) evaluated peripheral towns using indicators such as the number of lines, population within catchment areas, and service frequency. Other approaches integrate geographical, environmental, and operational factors within comprehensive assessment frameworks (Corazza, Favaretto 2019).

Recent research increasingly relies on GIS-based analyses of large urban and regional units and their comparison across different spatial contexts. In addition to conventional network-based approaches, Voronoi diagram methods are increasingly applied as an alternative spatial allocation technique, assigning each location to the nearest public transport stop based on defined proximity rules (Wang et al. 2014). While GTFS-based datasets and timetable-derived indicators form the backbone of many contemporary public transport accessibility and performance studies, they primarily capture service availability and temporal characteristics of transport systems. As such, they are not directly suited for analysing the walking pre-boarding stage of public transport use, which is the focus of the present study.

Based on these approaches, the present study adopts a two-dimensional framework of pedestrian accessibility that explicitly distinguishes between horizontal (distance-based) and vertical (terrain-related) components.

3. Methodology

3.1. Study areas

The analysis was conducted for two medium-sized Czech cities with pronounced terrain variability: Liberec and Zlín. Both cities function as regional centres and operate integrated public transport systems, yet they differ substantially in urban morphology and topographic context.

Liberec is situated in a mountainous environment in northern Czechia. The city's built-up area extends across steep slopes and valley floors, with an altitude range from approximately 301 m to 1,010 m above sea level, resulting in an overall elevation amplitude of nearly 710 m within the wider study area. This pronounced topographic variability strongly influences pedestrian movement and access conditions.

Zlín is located in eastern Czechia and is structured primarily along a central valley corridor with adjacent hillside development. The altitude of the study area ranges from approximately 184 m to 541 m above sea level, corresponding to an elevation amplitude of about 360 m, which is substantially lower than in Liberec but still significant in relation to everyday pedestrian mobility.

The spatial extent and location of both study areas are presented in Figure 1. As public transport systems in both cities operate beyond municipal boundaries, stops belonging to the integrated regional systems were included irrespective of administrative limits. To minimise boundary effects in network-based calculations, a 1 km buffer beyond the administrative boundaries of each city was applied to all spatial layers except population data, which were retained strictly within municipal boundaries.

3.2. Data sources

The analysis is based exclusively on open and reproducible data sources, ensuring transparency and methodological transferability. The pedestrian street network was derived from OpenStreetMap (OSM 2024), which provides detailed spatial information on urban transport infrastructure and was used solely as a spatial input for network-based calculations.

Public transport stop locations were obtained from official datasets provided by the relevant local and regional transport authorities operating within the

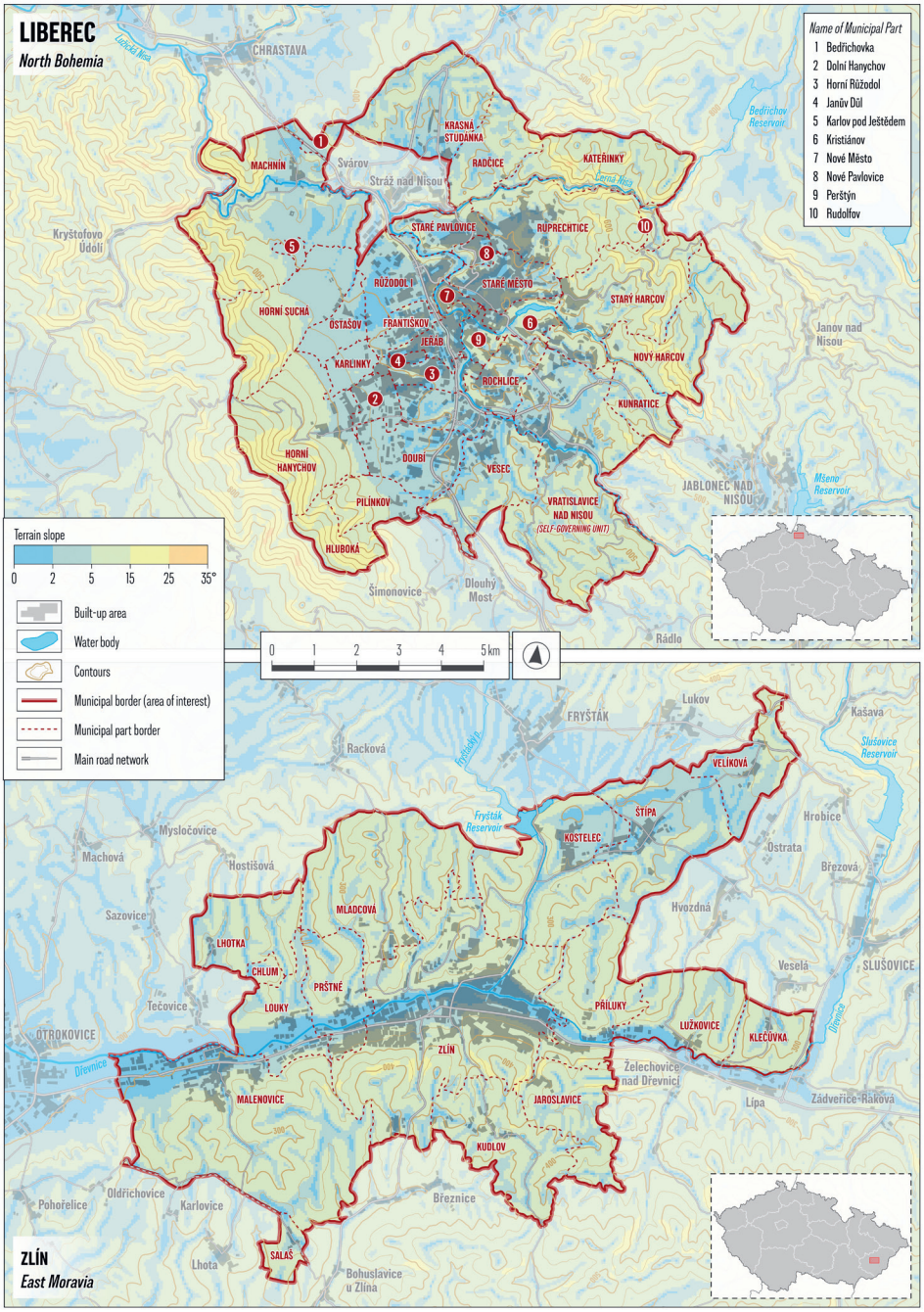


Fig. 1 – Location, delimitation, land-cover profile, and topographic context of the studied cities of Liberec and Zlín. Source: Author's own processing based on a combination of publicly available data (see Data sources).

integrated transport systems of Liberec and Zlín (DPMLJ 2024, DSZO 2024, IDOL 2024, IDZK 2024).

Terrain characteristics were represented using a digital elevation model from the Copernicus programme (OpenTopography 2024), which enables the derivation of elevation differences relevant for pedestrian accessibility analysis.

Population data at the building level, derived from address-point data with information on the number of residents based on the 2021 Population and Housing Census (CZSO 2024), were used to contextualise accessibility patterns within built-up areas and to ensure that the analysis focuses on spatially relevant residential environments rather than sparsely populated land. For analytical purposes, built-up areas were delineated using the Urban Atlas land-cover classification (Urban Atlas Land-Copernicus 2022), which was applied strictly as a land-cover mask to distinguish urbanised from non-urban areas.

3.3. Horizontal accessibility: network-based walking distance

Horizontal accessibility was operationalised as the shortest walking distance along the pedestrian network from any location to the nearest public transport stop. Network-based distance measures were employed to reflect actual pedestrian routes and spatial barriers (Foda, Osman 2010; El-Geneidy et al. 2013). Network-based modelling is therefore preferred over simple Euclidean buffers when the objective is to represent physically realistic pedestrian access conditions (Kraft 2016). Stop catchment areas were spatially generalised using Voronoi (Thiessen) polygons, where each polygon represents the area for which a given stop is the nearest according to the selected proximity rule (Wang et al. 2014).

For analytical clarity and inter-city comparability, horizontal accessibility was classified into three categories, where shorter network distance indicates better (higher-quality) accessibility and longer distance indicates worse accessibility:

- High horizontal accessibility (best): ≤400 m: (short walking distance; stop is easily reachable on foot)
- Medium horizontal accessibility: 401–800 m (moderate walking distance; accessibility is acceptable but may reduce convenience)
- Low horizontal accessibility (worst): >800 m (long walking distance; stop reachability is relatively poor).

These breakpoints correspond to walking-distance ranges frequently reported in empirical studies of pedestrian access to public transport and are used here as descriptive analytical classes rather than strict behavioural thresholds (El-Geneidy et al. 2013; Kaszczyszyn, Sypion-Dutkowska 2019). The same classification was applied in both cities to ensure comparability.

3.4. Vertical accessibility: elevation difference along pedestrian routes

In this study, the term "vertical accessibility" is used as a shorthand for terrain-related walking effort, operationalised through cumulative elevation difference along pedestrian routes rather than as an independent accessibility concept. Vertical accessibility was defined as the cumulative elevation difference between a given location and the nearest public transport stop, calculated along the pedestrian network. Elevation values were derived from the digital elevation model and assigned to network segments to compute route-based elevation change (Ford et al. 2015).

Previous research indicates that increasing elevation gain and slope reduce walking propensity and increase perceived effort, particularly in hilly urban environments (Djurhuus et al. 2014, Hino et al. 2013, Rissel et al. 2012, Su et al. 2023). Accordingly, vertical accessibility was included as a separate analytical dimension, where smaller elevation difference indicates better (higher-quality) accessibility and larger elevation difference indicates worse accessibility. Empirical evidence further shows that even moderate slope can reduce walking activity, justifying the treatment of elevation-related effort as a separate accessibility dimension (Meeder, Aebi, Weidmann 2017).

For interpretative purposes, vertical accessibility was grouped into three categories representing increasing terrain-related effort:

- High vertical accessibility (best): ≤10 m (minimal elevation change; low physical effort barrier)
- Medium vertical accessibility: 11–40 m (moderate elevation change; increased physical effort likely)
- Low vertical accessibility (worst): >40 m (substantial elevation change; strong terrain-related barrier).

These classes constitute an analytical classification designed to provide an interpretable three-level scale of terrain-related effort and to enable consistent cross-city comparison within the subsequent 3 × 3 synthetic typology. They do not represent universal physiological thresholds; rather, they support transparent comparative interpretation.

3.5. Synthetic classification of pedestrian accessibility

To capture cumulative pedestrian accessibility conditions, the three horizontal and three vertical categories were combined into a two-dimensional synthetic classification. Each spatial unit was assigned to one of nine categories representing all possible combinations:

1. High horizontal – High vertical (best overall pedestrian accessibility: short walk and minimal elevation change)
2. High horizontal – Medium vertical
3. High horizontal – Low vertical (short walk, but strong terrain barrier)
4. Medium horizontal – High vertical
5. Medium horizontal – Medium vertical
6. Medium horizontal – Low vertical
7. Low horizontal – High vertical (long walk, but minimal terrain barrier)
8. Low horizontal – Medium vertical
9. Low horizontal – Low vertical (worst overall pedestrian accessibility: long walk and strong terrain barrier).

This cross-classification preserves the analytical distinction between distance-related and terrain-related constraints and allows the identification of areas where limitations in both dimensions coincide, without collapsing them into a single compensatory score.

4. Results

4.1. Horizontal accessibility

Horizontal accessibility within the built-up areas of Liberec and Zlín is dominated by locations classified in the High horizontal accessibility category, defined by a network walking distance of up to 400 m from the nearest public transport stop.

In Liberec, areas with High horizontal accessibility cover 60.4% of the total built-up area. These areas form spatially extensive and largely continuous zones concentrated within the compact urban core and along the main axes of residential development. The Medium horizontal accessibility category (401–800 m) accounts for 29.0% of the built-up area and is typically arranged in transitional belts surrounding the High-accessibility zones. Areas classified as Low horizontal accessibility (>800 m) represent 10.6% of the built-up area and occur primarily as spatially fragmented patches located at the margins of the urbanised area.

In Zlín, the dominance of High horizontal accessibility is even more pronounced. Areas within this category cover 70.6% of the built-up area and form highly continuous spatial patterns reflecting the linear structure of the city and the dense alignment of public transport stops along its main development corridors. The Medium category represents 22.7% of the built-up area and is mainly associated with secondary residential areas adjacent to the primary urban structure. Low horizontal accessibility is limited to 6.8% of the built-up area and appears predominantly as small, isolated patches situated at the outer edges of the built-up area.

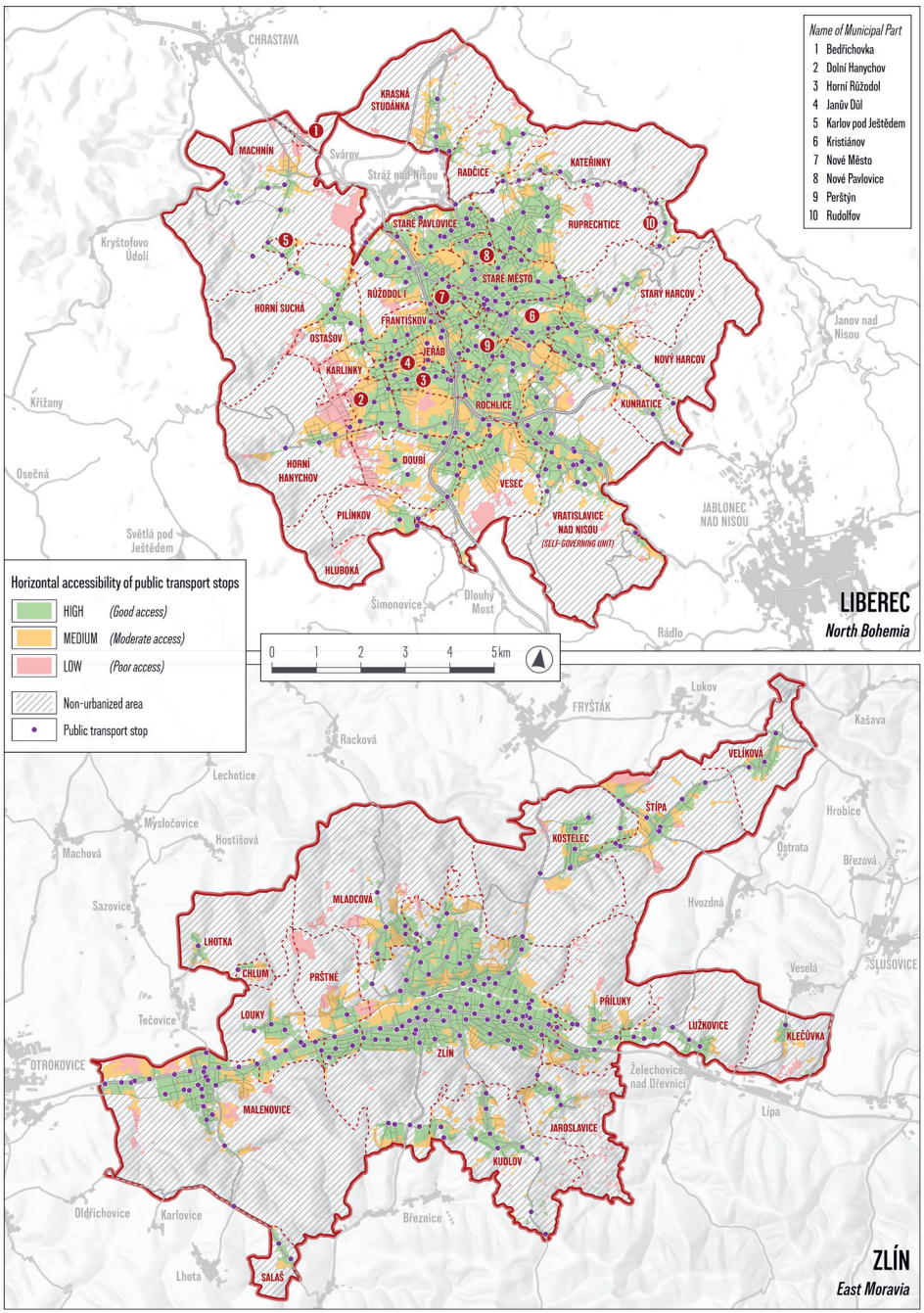


Fig. 2 – Horizontal (network-based) accessibility of public transport stops for urbanised areas of Liberec and Zlín in 2024. Source: Author's own processing based on a combination of publicly available data (see Data sources).

A comparison of both cities indicates that while High horizontal accessibility prevails in both cases, Liberec exhibits a more heterogeneous spatial pattern with a higher proportion of Medium and Low categories. In contrast, Zlín shows a stronger spatial continuity of High-accessibility areas within its built-up area. Beyond the general distribution of horizontal accessibility categories, Figure 2 reveals distinct transition zones between areas of high and medium accessibility, particularly at the interface between compact urban cores and more fragmented residential structures. In both cities, areas with High horizontal accessibility form relatively continuous zones in central parts of the built-up area, where stop density and pedestrian network connectivity are highest. These zones typically extend along main urban corridors and around central transport nodes.

In contrast, Medium horizontal accessibility often appears in spatially fragmented belts surrounding highly accessible cores. These belts represent transitional areas where walking distances remain moderate but the spatial continuity of high accessibility begins to weaken. Low horizontal accessibility is predominantly located at the edges of built-up areas and in morphologically fragmented zones, where stop spacing increases and pedestrian routes become less direct. In Liberec, these low-accessibility areas tend to form spatially dispersed clusters, whereas in Zlín they are more frequently arranged in elongated peripheral strips following the linear structure of the city.

4.2. Vertical accessibility

Vertical accessibility, expressed as cumulative elevation difference along pedestrian routes to the nearest public transport stop, displays a distinct but internally consistent spatial structure in both cities.

In Liberec, areas classified as High vertical accessibility (≤10 m elevation difference) account for 55.7% of the built-up area. These areas are predominantly located in morphologically flatter parts of the city and form relatively continuous zones within the urban fabric. The Medium vertical accessibility category (11–40 m) covers 39.2% of the built-up area and is widely distributed across the city, reflecting the prevalence of moderate slopes within residential areas. The Low vertical accessibility category (>40 m) represents 5.0% of the built-up area and is spatially concentrated in locations characterised by pronounced terrain variation, forming compact clusters rather than dispersed patches.

In Zlín, High vertical accessibility covers 58.1% of the built-up area and similarly forms extensive zones associated with flatter sections of the urban area. Medium vertical accessibility accounts for 35.9% of the built-up area and is spatially widespread, while Low vertical accessibility represents 6.0% of the built-up area. Areas within the Low category are concentrated in topographically

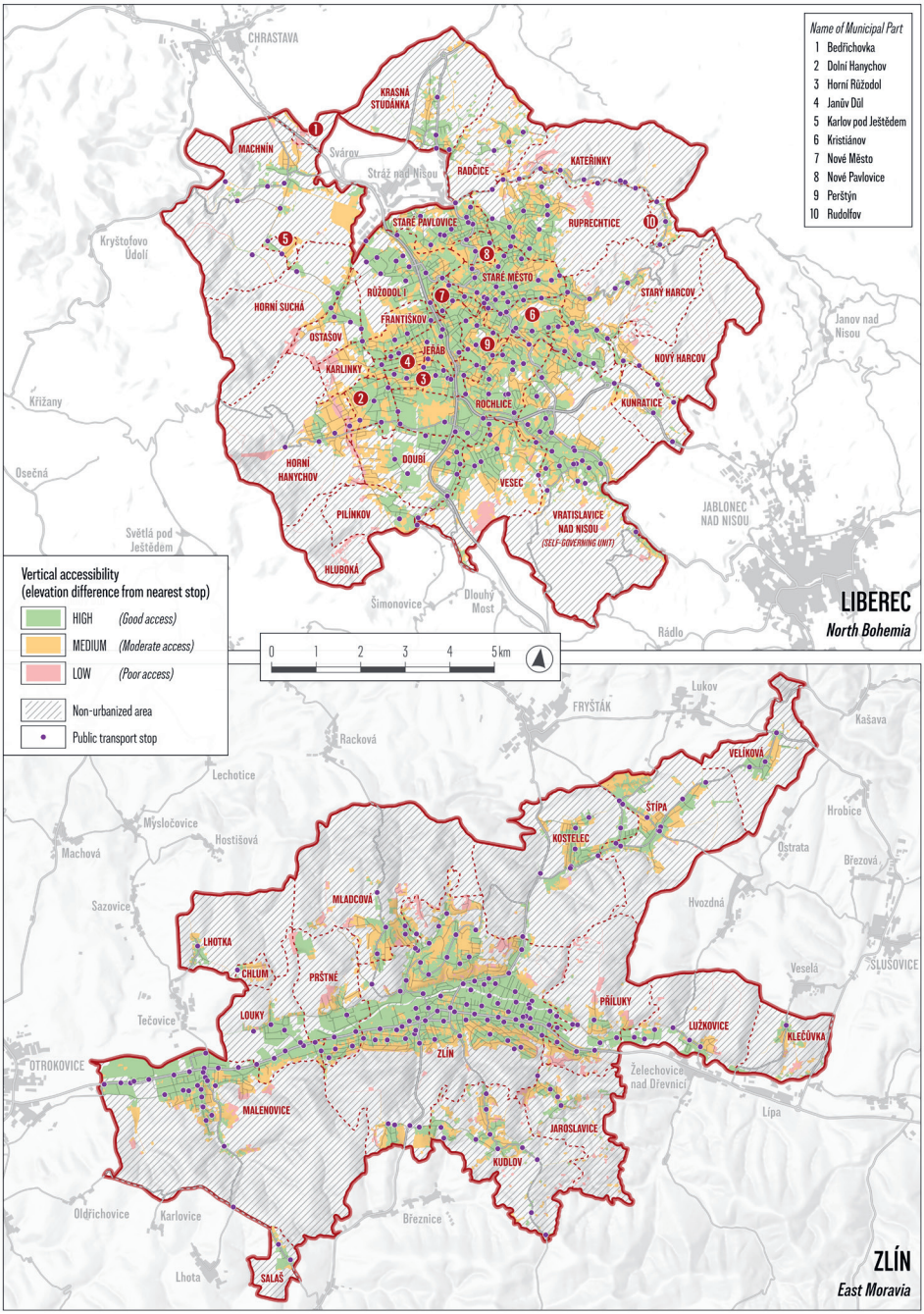


Fig. 3 – Vertical accessibility of public transport stops for urbanised areas of Liberec and Zlín in 2024. Source: Author's own processing based on a combination of publicly available data (see Data sources).

more demanding locations, where elevation differences between residential areas and public transport stops are substantial.

In both cities, the Medium vertical accessibility category constitutes a significant proportion of the built-up area, indicating that moderate terrain-related effort is a common characteristic of pedestrian access to public transport stops. Areas with Low vertical accessibility remain limited in spatial extent but are clearly identifiable as compact terrain-related clusters. The spatial configuration of vertical accessibility categories shown in Figure 3 exhibits a higher degree of internal heterogeneity than horizontal accessibility. High vertical accessibility is largely concentrated in valley floors and flatter sections of the built-up area, forming spatially continuous zones with minimal elevation change. These areas are particularly evident in Zlín, where low-relief corridors create extended zones of favourable vertical accessibility.

Medium vertical accessibility functions primarily as a transition category, occurring along slopes connecting valley floors with elevated residential areas. These zones often appear as fragmented or ribbon-like patterns rather than compact areas, reflecting gradual changes in terrain rather than abrupt breaks. Low vertical accessibility forms spatially coherent clusters in steeper hillside areas, especially in Liberec, where pronounced elevation differences generate large contiguous zones of terrain-related constraint. In Zlín, low vertical accessibility is more spatially limited and appears in smaller, discontinuous patches embedded within otherwise moderately accessible areas.

4.3. Synthetic accessibility

Synthetic accessibility integrates horizontal and vertical accessibility into a 3 × 3 classification, capturing cumulative pedestrian accessibility conditions across the built-up areas of Liberec and Zlín.

In Liberec, the largest share of the built-up area is occupied by combinations characterised by High or Medium horizontal accessibility combined with High or Medium vertical accessibility. These categories form spatially extensive and interconnected zones within the central parts of the city and along its main residential corridors. Combinations that include Low horizontal accessibility, Low vertical accessibility, or both are spatially limited and occur mainly at the periphery of the built-up area or in locations affected by pronounced terrain constraints.

In Zlín, favourable synthetic accessibility combinations are even more spatially dominant. Areas combining High horizontal and High vertical accessibility form large, continuous units structuring the core of the built-up area. Categories involving Medium accessibility levels are primarily located in transitional zones, while combinations including Low horizontal or Low vertical accessibility are

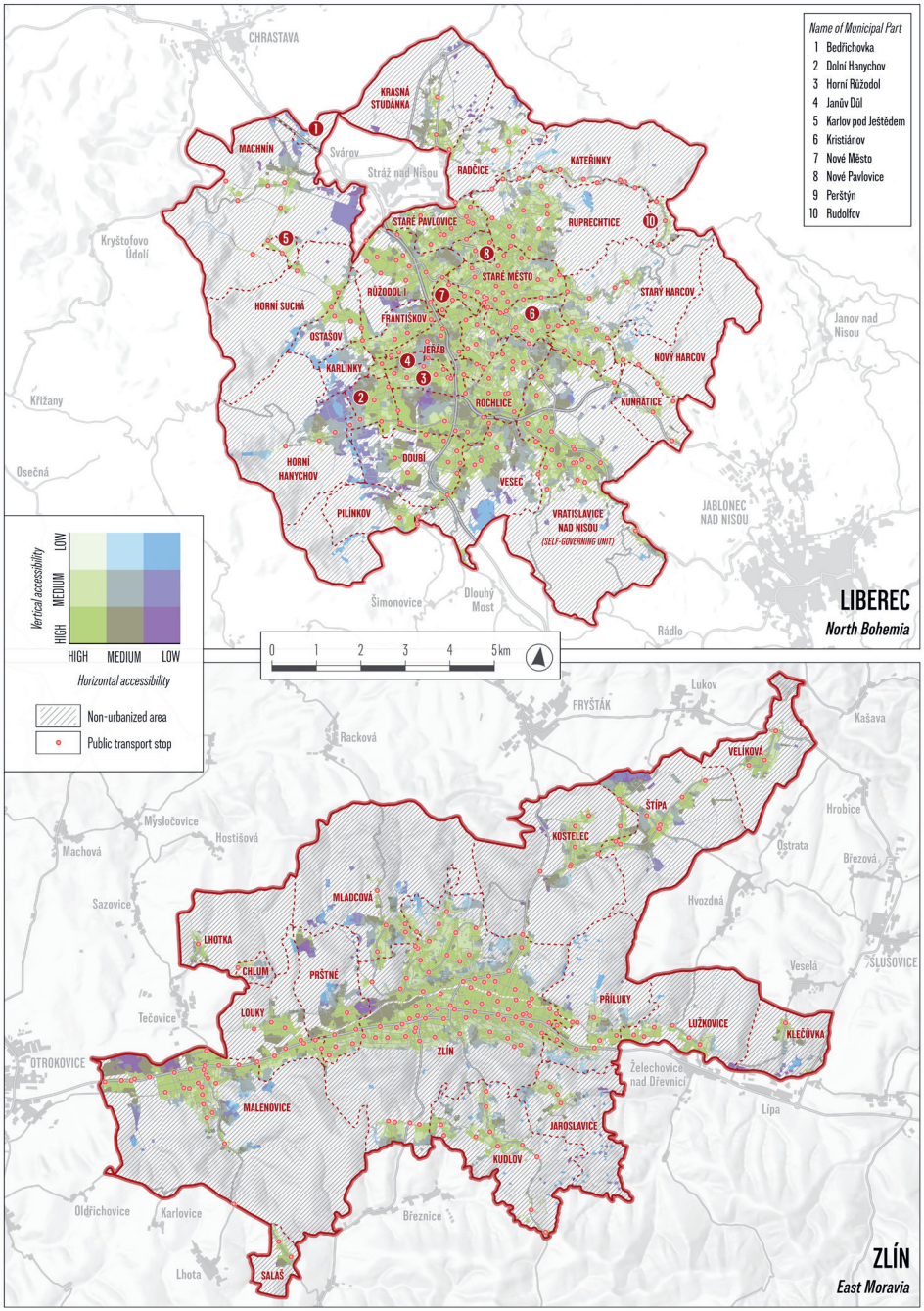


Fig. 4 – Synthetic accessibility of public transport stops for urbanised areas of Liberec and Zlín in 2024. Source: Author's own processing based on a combination of publicly available data (see Data sources).

restricted to small, fragmented patches situated at the edges of the urbanised area.

Across both cities, the synthetic accessibility classification reveals a clear spatial differentiation between areas where pedestrian access to public transport stops is constrained by distance, terrain, or both, and areas where such constraints are limited. While the overall structure of synthetic accessibility is similar in Liberec and Zlín, differences in spatial continuity and configuration reflect contrasts in urban form and topographic setting. The synthetic horizontal–vertical accessibility map presented in Figure 4 provides a comprehensive overview of cumulative pedestrian accessibility conditions by combining distance-related and terrain-related dimensions. The resulting 3 × 3 typology highlights pronounced differences not only between the two cities but also within their built-up areas.

Areas characterised by High horizontal – High vertical accessibility represent locations with both short walking distances and minimal elevation change. These areas form spatially continuous cores within the built-up area in both cities, although their extent differs markedly. In Zlín, high–high accessibility zones are more spatially coherent and elongated along the central valley axis, whereas in Liberec they are more fragmented and interspersed with zones affected by terrain-related constraints.

At the opposite end of the spectrum, Low horizontal – Low vertical accessibility identifies locations where long walking distances coincide with substantial elevation differences. These areas are spatially concentrated in peripheral and topographically complex sections of the built-up area. In Liberec, low–low accessibility zones form relatively extensive and contiguous clusters, reflecting the combined influence of dispersed development and steep terrain. In Zlín, such areas are less extensive and appear primarily as isolated pockets rather than large continuous zones.

Between these two extremes, a substantial share of the built-up area is characterised by intermediate combinations of horizontal and vertical accessibility. Among these, combinations involving High horizontal – Medium vertical accessibility are particularly prominent. These zones indicate areas where stops are spatially close but access involves moderate elevation change. In Liberec, such combinations are widespread along sloping residential neighbourhoods adjacent to central areas. In Zlín, they appear mainly along hillside development bordering the valley floor.

Combinations involving Medium horizontal – High vertical accessibility are also present, especially in flatter peripheral zones where walking distances are moderate but terrain-related barriers are limited. Conversely, Medium horizontal – Low vertical and Low horizontal – Medium vertical combinations represent areas where either distance or terrain begins to dominate accessibility conditions, often resulting in fragmented spatial patterns. These categories tend to form

transitional zones rather than compact areas, linking highly accessible cores with areas of cumulative constraint.

Overall, the synthetic classification reveals that uniformly favourable or unfavourable conditions represent only a portion of the built-up area. A significant share is instead characterised by mixed accessibility conditions, underscoring the importance of analysing horizontal and vertical dimensions jointly rather than in isolation.

4.4. Intermediate combinations and cumulative accessibility patterns

Beyond areas characterised by uniformly favourable or unfavourable conditions, the synthetic accessibility map reveals extensive zones defined by intermediate combinations of horizontal and vertical accessibility, which together account for a substantial share of the built-up areas in both cities (Fig. 4).

In Liberec, large areas combine High horizontal accessibility with Medium vertical accessibility, indicating locations where public transport stops are spatially close but pedestrian access involves moderate elevation differences. These zones form coherent spatial units, particularly in residential neighbourhoods situated on sloping terrain adjacent to the urban core. In contrast, areas combining Medium horizontal accessibility with High vertical accessibility are primarily located in flatter peripheral parts of the built-up area, where stop density is lower but terrain-related constraints are limited.

Zones characterised by Low accessibility in both dimensions form spatially coherent clusters in parts of the built-up area associated with dispersed development and pronounced terrain variability. Although these zones occupy a relatively small proportion of the built-up area, they represent locations where distance-related and terrain-related constraints co-occur.

In Zlín, intermediate accessibility combinations are generally less extensive and more spatially constrained. Areas combining High horizontal accessibility with Medium vertical accessibility form predominantly linear spatial patterns following hillside development adjacent to the central valley axis. Combinations involving Low horizontal accessibility are comparatively rare and occur mainly as small, fragmented patches at the edges of the built-up area.

4.5. Summary of spatial patterns of pedestrian accessibility

Taken together, the results demonstrate clear inter-city differences in the spatial structure of pedestrian accessibility to public transport stops within built-up areas. While both Liberec and Zlín exhibit substantial areas classified as having

favourable pedestrian accessibility conditions, Zlín is characterised by more spatially continuous patterns of combined horizontal and vertical accessibility. In contrast, Liberec displays a higher degree of spatial heterogeneity, primarily associated with terrain-related variability.

The synthetic horizontal–vertical accessibility framework provides a spatially explicit representation of cumulative pedestrian accessibility conditions and constitutes the core empirical output of this study. The identified patterns summarise the distribution and internal differentiation of pedestrian accessibility within the built-up areas of both cities and form the empirical basis for further interpretation in the discussion section.

5. Discussion

5.1. Interpretation of horizontal and vertical accessibility patterns

The results demonstrate that pedestrian accessibility to public transport stops cannot be adequately captured by a single indicator. The explicit separation of horizontal (network-based distance) and vertical (terrain-related) accessibility reveals structurally different accessibility patterns in Liberec and Zlín, despite both cities being of comparable size and operating integrated public transport systems.

In terms of horizontal accessibility, the dominance of areas classified as High accessibility in both cities corresponds with findings from studies focusing on walking distance to public transport stops (Foda, Osman 2010; Kaszczyszyn, Sypion-Dutkowska 2019). However, the spatial configuration of these areas differs substantially. Zlín exhibits a more spatially continuous pattern of high horizontal accessibility, reflecting its linear urban structure and concentrated alignment of stops along the valley axis. In contrast, Liberec displays greater spatial heterogeneity, with a higher proportion of Medium and Low horizontal accessibility within the built-up area.

The analysis of vertical accessibility highlights terrain as an independent and structurally significant constraint. Liberec is characterised by more extensive and contiguous clusters of low vertical accessibility, corresponding to pronounced elevation differences within the urban fabric. Similar terrain-related effects have been identified in studies examining the influence of hypsometric conditions on pedestrian access to public transport (Djurhuus et al. 2014, Rissel et al. 2012, Su et al. 2023). In Zlín, terrain-related constraints are more spatially limited and embedded within otherwise accessible zones, resulting in lower overall heterogeneity.

Taken together, these findings confirm that horizontal and vertical dimensions of pedestrian accessibility differ not only in magnitude but also in their spatial configuration, thereby addressing the first research question.

5.2. Terrain as a modifying factor of pedestrian accessibility

The second research question addressed the extent to which terrain influences spatial patterns of pedestrian accessibility within built-up areas. The results indicate that terrain functions not merely as a background characteristic but as a modifying factor that can significantly alter accessibility outcomes derived from distance-based measures.

In Liberec, short network distances to public transport stops frequently coincide with substantial elevation differences, producing accessibility conditions that would be classified as favourable under distance-only approaches but appear less favourable when terrain is considered. Comparable discrepancies between distance-based and terrain-adjusted accessibility have been reported in previous studies integrating elevation or slope into accessibility assessment (Ford et al. 2015, Su et al. 2023). This suggests that distance-based indicators alone may systematically overestimate pedestrian accessibility in topographically complex cities.

In Zlín, terrain-related constraints are more closely aligned with the overall urban structure, resulting in fewer locations where distance-based and terrain-based indicators diverge sharply. This observation supports findings by Hino et al. (2013), who emphasise the role of urban morphology in mediating the impact of terrain on pedestrian accessibility.

5.3. Added value and positioning of the synthetic accessibility framework

The third research question examined whether combining horizontal and vertical accessibility dimensions can reveal cumulative physical barriers that remain hidden when each dimension is analysed separately. The synthetic horizontal–vertical accessibility typology represents the principal empirical contribution of this study.

The results show that areas characterised by uniformly favourable (High–High) or uniformly unfavourable (Low–Low) conditions account for only a limited share of the built-up area. A substantial proportion of urban space is instead defined by intermediate combinations, such as High horizontal – Medium vertical or Medium horizontal – Low vertical accessibility. These mixed configurations identify locations where pedestrian accessibility is constrained by one dimension but not the other.

This finding is consistent with arguments that multidimensional accessibility measures provide a more nuanced and spatially explicit representation of access conditions than single-indicator approaches (Sha Al Mamun, Lownes 2011; Żochowska et al. 2022). Importantly, the non-compensatory structure of the proposed framework preserves the analytical distinction between distance-related and terrain-related constraints, avoiding the masking effects associated with aggregated composite indices.

A substantial body of accessibility research has focused on temporal variability, operational performance, and service-based accessibility, often relying on timetable-derived or GTFS-based indicators (Goliszek, Połom 2016; Goliszek 2019; Goliszek 2021; Prommaharaj et al. 2020). Dynamic approaches enable the analysis of peak-hour deviations, temporal mismatches between supply and demand, and service reliability (Goch et al. 2018; Tao, Rohde, Corcoran 2014). While such methods provide valuable insights into service accessibility, they do not explicitly capture the physical effort required to reach the public transport system itself.

Similarly, network connectivity measures and composite accessibility indices integrate multiple dimensions – such as distance, frequency, and network structure – into single indicators, either through graph-based connectivity metrics or through aggregated accessibility scores (Chowdhury, Ceder, Velty 2014; Háznagy et al. 2015; Tiran, Mladenović, Koblar 2015). Although these approaches are useful for strategic planning and benchmarking, they may obscure the specific mechanisms through which pedestrian accessibility constraints arise.

In contrast, the framework applied in this study deliberately avoids collapsing heterogeneous dimensions into a compensatory score. By maintaining an explicit distinction between horizontal and vertical components of pedestrian accessibility, the approach enables the identification of cumulative barriers that remain concealed in aggregated indices. This methodological positioning aligns with calls for greater conceptual clarity and transparency in accessibility research (Corazza, Favaretto 2019).

5.4. Methodological implications and transferability

From a methodological perspective, the study demonstrates the feasibility of modelling pedestrian accessibility using open and reproducible data sources. The reliance on OpenStreetMap, Copernicus elevation data, and official public transport stop datasets enables straightforward replication across different urban contexts without the need for proprietary data or specialised software environments.

Recent studies have highlighted the potential of open GIS tools and openly available datasets for analysing public transport accessibility and performance at various spatial scales (Andrei, Luca 2021; Alamri et al. 2023). By combining widely accessible data sources with a transparent analytical workflow, the proposed framework offers a transferable methodological template for medium-sized cities with complex terrain. The transferability of the framework is supported by its reliance on globally available spatial data, a clearly defined analytical workflow, and a non-compensatory classification logic, although specific threshold values may require contextual calibration to local topographic conditions and walking norms.

5.5. Limitations and directions for further research

Several limitations of the study should be acknowledged. First, the analysis focuses exclusively on pedestrian accessibility to public transport stops and does not incorporate service characteristics such as frequency, reliability, or timetable coordination. While this represents a deliberate conceptual choice, it limits direct comparability with studies adopting broader definitions of public transport accessibility.

Second, vertical accessibility is operationalised using cumulative elevation difference and does not explicitly account for slope variability or walking speed. More refined indicators, such as slope-weighted walking time, could further enhance the representation of terrain-related effort (Ford et al. 2015).

Third, the analysis does not incorporate user-specific characteristics or perceived accessibility, which have been shown to influence transport behaviour and accessibility outcomes (Lättman, Friman, Olsson 2016). Integrating perception-based data and socio-demographic characteristics represents an important avenue for future research.

Although population data were available at the building level, the analysis deliberately focuses on spatial patterns of pedestrian accessibility within built-up areas rather than on population-weighted accessibility indicators. This choice reflects the study's emphasis on the physical structure of accessibility conditions rather than on distributional or equity-based outcomes.

5.6. Positioning within the broader accessibility literature

By explicitly distinguishing pedestrian stop accessibility from service-based accessibility, the study contributes to ongoing debates regarding the conceptual clarity of accessibility research. As noted in the literature, studies labelled as addressing "public transport accessibility" often examine fundamentally different phenomena, ranging from infrastructure proximity to service performance and broader issues of social inclusion (Corazza, Favaretto 2019). From an equity-oriented perspective, accessibility analyses are increasingly used to identify spatial disparities and transport disadvantage, reinforcing the need to distinguish analytically between physical access conditions and service-based accessibility outcomes (Eldeeeb, El-Baky, Masoumi 2024; Pereira, Schwanen, Banister 2017).

The present study positions pedestrian accessibility as a necessary precondition for effective public transport use rather than as a substitute for service-based measures. In doing so, it complements existing accessibility frameworks and provides a focused analytical tool for examining the spatial foundations of public transport accessibility.

6. Conclusion

This study set out to examine the pedestrian accessibility of public transport stops by explicitly distinguishing between horizontal (network-based walking distance) and vertical (terrain-related elevation difference) components. By isolating the pre-boarding stage of public transport use from broader notions of service accessibility, the analysis addressed a foundational yet often underexplored dimension of everyday mobility: the physical effort required to reach the nearest stop on foot.

Using Liberec and Zlín as comparative case studies, the results demonstrated that pedestrian accessibility to public transport stops cannot be adequately characterised by horizontal distance alone. Although both cities exhibit substantial areas with close proximity to stops, the incorporation of terrain-related constraints revealed pronounced differences in the internal structure and spatial continuity of accessibility conditions. These findings directly respond to the first research objective formulated in the introduction, confirming that horizontal and vertical dimensions of pedestrian accessibility differ not only in magnitude but also in their spatial configuration across cities.

The analysis further showed that terrain acts as a significant modifying factor of pedestrian accessibility rather than a secondary background condition. In Liberec, elevation differences frequently intersect with areas of otherwise favourable proximity to stops, producing heterogeneous accessibility patterns within the built-up area. In Zlín, terrain-related constraints are more closely aligned with the city's linear urban structure and are spatially more contained. This comparison addresses the second research question and highlights the importance of considering the interaction between urban morphology and topographic conditions when assessing pedestrian access to public transport.

A central contribution of the study lies in the development and application of a synthetic horizontal–vertical accessibility framework. By combining distance-related and terrain-related dimensions in a non-compensatory manner, the framework revealed spatial configurations – such as short-but-steep or far-but-flat areas – that remain concealed when each dimension is analysed separately. The identification of such cumulative physical barriers responds directly to the third research question and underscores the analytical value of multidimensional approaches to pedestrian accessibility.

The fourth research question concerned the transferability of the proposed framework to other urban contexts. The application of a uniform analytical logic and classification scheme to two structurally different cities demonstrated that the framework is transferable in structure and methodological logic, even though specific threshold values may require contextual adaptation. A key strength of the approach lies in its reliance on open and widely available data sources, including OpenStreetMap, Copernicus elevation data, and official public transport stop

datasets. This reliance enhances transparency, reproducibility, and applicability across different cities without the need for proprietary data or specialised software environments.

Beyond its empirical findings, the study contributes conceptually by clarifying the distinction between pedestrian stop accessibility and broader forms of public transport accessibility that incorporate service characteristics such as frequency, reliability, or travel time. By positioning pedestrian accessibility as a necessary precondition for effective public transport use rather than a substitute for service-based measures, the paper helps to sharpen conceptual boundaries within accessibility research and supports more targeted analytical and planning applications.

Several limitations of the study should be acknowledged. The analysis focuses exclusively on pedestrian accessibility and does not account for service-level characteristics or user-specific factors such as age, mobility constraints, or perceived effort. While this represents a deliberate analytical choice, future research could integrate the proposed framework with timetable-based accessibility measures, slope-weighted walking time, or socio-demographic data to provide a more comprehensive assessment of accessibility and equity implications.

In summary, this study demonstrates that a two-dimensional horizontal–vertical framework provides a more nuanced and spatially explicit understanding of pedestrian accessibility to public transport stops than conventional distance-based approaches. By revealing cumulative accessibility constraints and highlighting differences between cities with similar overall characteristics, the proposed framework offers a robust and transferable tool for comparative research and context-sensitive urban transport analysis.

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