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Land Use Change from Non-urban to Urban Areas

Problems, Challenges and Opportunities

Edited by
Víctor Hugo González-Jaramillo and Antonio Novelli

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Article

Establishment of the Baseline for the IWRM in the Ecuadorian Andean Basins: Land Use Change, Water Recharge, Meteorological Forecast and Hydrological Modeling

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Abstract: This study was conducted in the Zamora Huayco (ZH) river basin, located in the inter-Andean region of southern Ecuador. The objective was to describe, through land use/land cover change (LUCC), the natural physical processes under current conditions and to project them to 2029. Moreover, temperature and precipitation forecasts were estimated to detail possible effects of climate change. Using remote sensing techniques, satellite images were processed to prepare a projection to 2029. Water recharge was estimated considering the effects of slope, groundcover, and soil texture. Flash floods were estimated using lumped models, concatenating the information to HEC RAS. Water availability was estimated with a semi-distributed hydrological model (SWAT). Precipitation and temperature data were forecasted using autoregressive and exponential smoothing models. Under the forecast, forest and shrub covers show a growth of 6.6%, water recharge projects an increase of 7.16%. Flood flows suffer a reduction of up to 16.54%, and the flow regime with a 90% of probability of exceedance is 1.85% (7.72 l/s) higher for 2029 than for the 2019 scenario, so an improvement in flow regulation is evident. Forecasts show an increase in average temperature of 0.11 °C and 15.63% in extreme rainfall by 2029. Therefore, intervention strategies in Andean basins should be supported by prospective studies that use these key variables of the system for an integrated management of water resources.

Keywords: land use/land cover change; water recharge; flooding; meteorological forecast; hydrological response; IWRM

1. Introduction

Land use/land cover change (LUCC) impacts on various natural physical processes within watersheds have been extensively investigated worldwide [1,2]. The location of the Andean basins within intervention policies has also been the subject of analysis over the last several decades [3–5]. Changes and distribution of land use have an important influence on natural processes in a basin [1,2]. Water recharge, for example, shows sensitivity to different coverage due to the different infiltration rates that can occur under the same precipitation conditions [6,7], which is the reason why a change or alteration must be analyzed to evaluate its consequences. That is why water recharge was estimated in order to evaluate the effects that LUCC would have on it. In addition, the areas of the basin that favored it were spatially represented [8–10].

Another hydrological process that is influenced by LUCC are the flows associated with high intensity rains [11]; therefore, its analysis implies an element of judgment when making decisions at territorial level. The hydraulic simulation of flash floods was carried out to denote the impact of LUCC, generating information on flows and flood plains along the main channel [11] and giving technical support to the implementation of strategies associated with flood vulnerability reduction accompanied by land use planning policies and non-disruptive engineering practices [12].

Simulating the hydrological response of a basin under land use/land cover (LULC) scenarios is another key element for the integrated management of water resources [13], because it allows for the impact of LULC on the outlet flow of the basin [1,14,15]. This input is also the basis for the application of territorial policies and programs for the conservation of water sources.

Some studies have explored the relationship of LUCC with the hydrological response in basins. For example, for flow reproduction and calculation of sediment production in the Catamayo-Chira binational basin, the semi-distributed model called the Soil and Water Assessment Tool (SWAT) was implemented [16]. Similarly, the SWAT model was applied, obtaining satisfactory results at the Calumpang basin in Philippines [1].

In this study, the SWAT model is implemented for flow simulation, taking as scenarios: (a) a classified map of LULC in 2019, and (b) a projected map of LULC in 2029. With the generated hydrographs, flow duration curves (FDC) were prepared and the probability of exceedance of different flow values was analyzed for both scenarios.

Forecasted hydro-climatic information is scarce in the study region. In order to solve this need, the mean temperature and precipitation were forecasted through autoregressive and exponential smoothing models, widely used in annual series and meteorological variables [17–20]. Because these climatic data strongly influenced [21], their effects should be considered irreducible (even with the associated uncertainties), so intervention plans and adaptive strategies should be proposed to help mitigate these effects [22].

Our study focuses on the integrated water resources management (IWRM) in Andean basins. The ZH basin was used as a study case because of the interventions carried out there at the level of political institutions by decision-makers. Land use practices on the basin have been restricted in the last several years mainly due to municipal intervention policies for water sources preservation; a regional water fund operates in the area, ensuring that anthropogenic activities are not being carried out in areas considered as water recharge [23]. The basin has the also particularity of being located in a transition zone between a consolidated urban sector to a National Park [24].

The first results have been divided into two parts: this article, whose objective is to describe LUCC with some natural physical processes such as water recharge, flash floods, and water availability; temperature and precipitation forecasts have also been prepared to detail the possible effects of climate change to a horizon of 10 years. The second part is detailed in an article whose objective is to make a prospective analysis of water management in the ZH basin, including physical, socio-economic, and political-institutional variables, generating future scenarios and detailing strategies to reach a target horizon.

2. Materials and Methods

2.1. Study Area

The Zamora Huayco (ZH) river basin (3806 ha) is located in the inter-Andean region of the Loja province in southern Ecuador between the geographic coordinates 3°59′42″–4°04′03″ S and 79°11′54″–79°07′35″ W (Figure 1). The elevation of the basin ranges between 2120 and 3420 m asl, and its average slope is 0.65 m/m.

The basin's climate is cold temperate mesothermal [25], characterized by an average annual temperature between 12 and 18 °C and average annual precipitation of 1047 mm. The wet season occurs from December to May and the dry season from June to November [26].

The basin has a predominantly forested vegetation. Since 1976, the forests of the basin have decreased by 19.3% [27]. The upper zone of the ZH basin is shared with the buffer zone of the Podocarpus National Park (PNP) [24]. Since the 1960s, natural vegetation near to PNP has been extensively removed to create pastures and farmland [27,28]. The main productive activities in the basin are agriculture and cattle raising [24,29]. In the ZH basin, there are two water catchments for potabilization that supply approximately 50% of the demand of the city of Loja with 450 l/s [30].

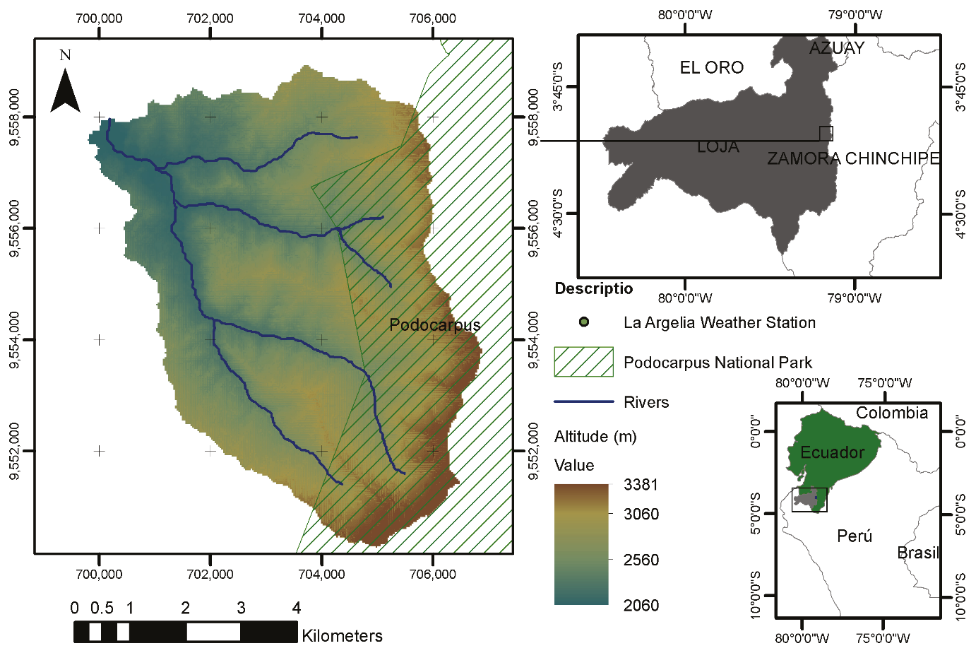

Figure 1. Location of the Zamora Huayco, an Andean basin in southern Ecuador.

2.2. Land Use/Land Cover Change (LUCC)

Using remote sensing techniques, satellite images were processed to analyze LUCC. Three images were obtained: Landsat7 ETM (11 September 2009), Landsat8 OLI_TIRS (20 September 2017), and Sentinel 2B Level 1C (31 July 2019), which were ortho-rectified [31,32]. The satellite's geometric coincidence with two temporarily invariable control points was verified, taking as reference an aerial photograph obtained from the SigTierras portal [33].

For the Landsat7 ETM and Landsat8 OLI_TIR images, the conversion to reflectance was performed to top of atmosphere (TOA) and to brightness temperature according to L. Congedo (2016). For the Sentinel 2B Level 1C image, the conversion was not performed as it is already scaled in TOA [32]. In the three images, the atmospheric correction Dark Object Subtraction (DOS) was performed [34]. In the three images, the topographic correction was also applied due to shading (CTS), using the Lambertian Cosine Model proposed by Teillet [35], for which it was necessary to determine the angle of incidence according to [36].

Radiometrically Terrain Corrected (RTC) data from DEM ALOS PALSAR, purchased from the Alaska Satellite Facility (ASF) Fairbanks, with a spatial resolution of 12.5 m, geocoded and radiometric corrected in its geographical extension [37], was used to carry out the CTS. LULC was obtained by supervised classification, using the method of the maximum likelihood classification algorithm based on Bayes' theorem, of the three images previously processed. Three LULC categories of anthropogenic type and three of natural-physical type were classified.

For LUCC analysis, the procedure was analogous to that proposed by [38]. First, coverages obtained for the years 2009 and 2017 were analyzed; the quantitative change represented graphically in terms of gains and losses by categories was obtained.

As explanatory variables, maps were used showing the exchanges between the categories of grasslands and shrub vegetation, forest and bare soil, crops and grasslands, in addition to forest and crops. Additionally, a map containing the spatial trend of change was made, from forest to shrub vegetation, in order to generalize the pattern of change between these categories [39]. A ninth-degree polynomial order was considered.

Changes below 600 cells were ignored, in order to limit the transition model to 9 sub- transitions. The sub-transitions selected were: shrub vegetation to forest, bare soil to shrub vegetation, bare soil to grassland, bare soil to forest, grassland to shrub vegetation, grassland to forest, forest to shrub vegetation, forest to grassland, and grassland to crops.

The objective of the transition model is to create potential transition maps with a high degree of precision to execute the change model [38]. Transitions were grouped into a single sub-model; also, 6 explanatory variables were included.

The first explanatory variable was the shrub vegetation cover contained in the 2009 map. This model was included as a dynamic component that is recalculated over time during the course of the prediction. The other explanatory variables were included as static components, corresponding to the spatial trend maps and exchanges between categories previously generated.

Physical restrictions of any kind have not been considered, because they are not necessary in a simple prediction [38]. For the transition model, the Multi-Layer Perceptron (MLP) algorithm has been applied, based on the Backpropagation (BP) algorithm, which is a supervised training algorithm [40]. For the change model, Markov chains were applied, generating a matrix with the probability that each category of land cover will change to any other category [38]. A validation was performed with the map generated for the year 2019.

To verify the image projected to 2019, a confusion matrix was performed and the kappa coefficient was determined. The confusion matrix shows the relationship between the reference data (2019 classified map) and the data to be evaluated (2019 projected map), constructing a matrix comparison of the classes verifying the overall accuracy of the projection by relating the number of points correctly assigned to the total [36]. The kappa coefficient evaluates the degree of agreement between categorical variables and takes into account the coincidences by randomness and by decision criteria; that is, it shows the degree of agreement that exists above random [41].

Similar to what was performed by [7,42], following the same conditions used in the 2009–2017 projection, the land use map for the year 2029 was generated, based on the 2009 and 2019 maps. The 2019 classified map containing LULC is called Scenario (1), and the 2029 projected map containing LULC is called Scenario (2).

2.3. Hydric Recharge Estimation

The multi-year average hydric recharge of the ZH basin was estimated, following the methodology set forth by [8] and also considering the infiltration criteria of [10], taking into account multi-year average precipitation, evapotranspiration (ET), basic soil infiltration rate, LULC, and terrain relief. The multi-year average rainfall was determined using data from La Argelia meteorological station over a 30-year period (1985 to 2015). Potential evapotranspiration (ET_P) was determined through Hargreaves and Samani [43], who considered precipitation over the same time period (30 years).

As there is a correlation between the crop coefficient (K_c) and the $NDVI$ [44–47], K_c was deducted by applying the expression [44]:

$$K_c = 1.84\ NDVI^2 - 1.03\ NDVI + 0.42 \quad (1)$$

$NDVI$ was obtained from the Landsat8 OLI_TIRS image (20 September 2017). The multi-year average value of the calculated ETP was multiplied by the K_c value to estimate the actual ET [48].

A slope map was generated using the DEM ALOS PALSAR RTC. This map was classified into 6 different categories (limits of <15, 15, 30, 50, 70, and >70%), assigning a coefficient to each. (k_p), known as the surface runoff coefficient, indicates the fraction that infiltrates due to the effect of slope [9]. Its value was taken from the table proposed by [8].

To each land use scenario (2019 and 2029) was assigned a value, named the land use coefficient (k_v), which represents the fraction that infiltrates due to the effect of the vegetation cover [9]. Its values were extracted from the table proposed by [8].

The infiltration fraction related to soil texture (kf_c) was estimated using the following expression [10]:

$$kf_c = 0.267\ln(fc) - 0.000154(fc) - 0.723 \quad (2)$$

where fc is the soil basic infiltration rate in mm/d. This was estimated using the Green-Ampt infiltration model [49], from soil data sampled in the ZH basin by [27].

According to [27], the most common soil texture in the study area is loam, with a bulk density from 0.07–1.09 g/cm^3, organic carbon percentage from 1.66 to 5.98%, field capacity around 25.34%, and hydraulic conductivity that varies between 4.6 and 8.9 mm/h in a saturated state.

The multi-year average recharge, for LULC Scenarios (1) and (2), was determined using the following expression [8,10]:

$$R = (Pma - ET_P \cdot K_c)(k_p + k_v + kf_c) \quad (3)$$

where Pma is the multi-year average precipitation corresponding to the La Argelia station. ET_P is the potential precipitation determined through Hargreaves and Samani.

2.4. Flash Flood Risk Assessment

Precipitation records of 51 years (from 1964 to 2015) were prepared and the data were controlled, corrected, and revised; the maximum precipitation in 24 h for each year was ordered. Different distribution functions were evaluated. Their precision was estimated through accumulated error, the Nash–Sutcliffe coefficient (NSE) and root mean square error (RMSE). Using GIS, physical parameters of the basin were determined such as area, average slope, channel length, channel slope, etc. Concentration time was estimated by Kirpich, Clark, and Temez [50,51].

For subsequent calculations, the concentration time was considered equal to design storm time. The maximum intensity was determined with this time, taking into account the intensity, duration, and frequency equations based on the maximum rainfall in 24 h corresponding to La Argelia station [52].

The hydrological response to extreme events was evaluated through synthetic unit hydrographs of the concentrated models Ven Te Chow, Snyder, Triangular SCS, and Temez. The mean and standard deviation of these results were calculated to assess dispersion and choose a model whose response is close to the mean. Curve numbers (CN) for scenario (1) and scenario (2) was determined using its respective land cover maps, taking into account the soil data provided by [27] through GIS.

Information corresponding to paths and flows was input to the HEC RAS hydraulic model and the outputs obtained were returned to GIS [11,53]. For the hydraulic evaluation, the main channel was divided into 29 cross sections. The roughness coefficients of the main channel and the banks were determined with the procedure explained by the USGS [54,55].

2.5. Meteorological Forecast

Meteorological information was taken from La Argelia station records, analogously to the method undertaken by [56]. It was developed with the annual mean temperature values; in addition, we obtained the values of maximum precipitation in 24 h of each month, and they were averaged obtaining an annual mean. These parameters will be referred to as T_average and Pmax_average from now on in the document.

The maximum precipitation data in 24 h of each month were prepared, since, as indicated by [21], one of the effects to a near horizon due to the increase of temperatures in high Andean basins is the increase in high intensity rainfall. These two annual series were forecast for the year 2029 using the Integrated Autoregressive Moving Average (ARIMA) model, the Holt exponential smoothing model (double exponent), and the Holt–Winters model (triple exponent). These models seek to describe the future behavior of the variables in relation to their past values [18].

The ARIMA model was used to predict series of a single variable. These are optimal with data series without seasonal variation, so they are widely used in annual series and meteorological variables [18–20]. In the ARIMA model (p, d, q), p indicates the correlation between current values and their immediate past values (autoregressive component), d indicates the order of differentiation to be applied in the series so that it becomes seasonal, and q indicates the moving average component order [17,18,57].

The double exponential model (Holt) considers an exponential smoothing, an estimation of trend, and a forecast. It involves adjusting the trend of the series at the end of each period. Triple Exponential Smoothing (Holt–Winters) adds an additional seasonality component to Holt model [58].

Series were attempted to be temporarily consistent, from 1985 to 2015. For the ARIMA model and the exponential smoothing models, their parameters were estimated (autoregressive components, seasonality, moving average and functional transformations), selecting the appropriate ones according to the best fit [17,19,56,57]. In order to verify the precision of the model and the chosen parameters, statistical measures such as the mean absolute error (MAE) and the root mean square error (RMSE) were determined.

2.6. Water Availability Estimation

In order to estimate water availability, a semi-distributed hydrological modeling was carried out through SWAT, with LULC scenarios (1) and (2). With the flow values simulated, FDC were determined for each scenario. For the modelling, DEM ALOS PALSAR RTC was used and weather information was collected from La Argelia station. The model worked with 24 h precipitation and daily average values of maximum temperature, minimum temperature, relative humidity, and wind speed. Solar radiation was estimated applying the Hargreaves and Samani equations [43].

Monthly climatic parameters required by SWAT were calculated using the SWAT Weather Database tool [59], similar to what was done by [14]. Missing values were input as −99.0, so that SWAT can estimate data for that day [60]. A soil map was generated from the soil sampling data provided by [27], data was supplemented and adapted to SWAT requirements, and the K_{USLE} variable was determined by applying Williams equations [60]. As these are soils with unique characteristics, they were added to the SWAT user-soil database table, analogously to the research carried out by [61].

The LULC maps of 2019 and 2029 contained in scenarios (1) and (2) respectively were used for analysis. Coverages of forest, shrub vegetation, grassland, bare soil, agriculture, and urban life were concatenated to SWAT database coverages considering similarity between characteristics and parameters, similar to what was done by [16].

The slopes range considered for the definition of the hydrological response units (HRU) were selected based on those established by [8], which respond to an adaptation of the considerations made by [9] considering water infiltration easiness into the ground due to slope, similar to what was performed by [62].

Simulation was performed considering a daily periodicity. The number of years of omission (NYSKIP) was entered, which is necessary to train the model; in this case 5 years was input as NYSKIP. As a general rule, a minimum of 3 NYSKIP is an acceptable heating period [1]. The simulated flow begins in 1991 and ends in 2015.

In order to analyze the occurrence and frequency of the flow at the exit of the basin, and to be able to predict its availability, FDC were generated for each scenario [63,64]. This theoretical curve has been determined from modeled daily average data.

3. Results

3.1. LULC and LUCC

First, when analyzing the gains and losses by categories, it was evident that the most important changes between 2009 and 2017 occurred in relation to forest and grassland cover. When analyzing these categories individually, in the forest cover the most significant exchanges occurred with the categories of shrub vegetation, bare soil, and crops; for grassland cover, the categories with the most important exchanges were crops and shrub vegetation.

It is for this reason that the explanatory variables, and the projection's transition model to year 2019 based on the years 2009 and 2017, included maps with exchanges between categories of grasslands and shrub vegetation, forest and bare soil, crops and grasslands, in addition to forest and crops. Moreover, because of the evident pattern of change between forest and shrub vegetation, this was included in the transition model as a map of spatial trend of change.

The spatial trend of change map was generated with a ninth-degree polynomial order, because lower polynomial orders do not significantly influence the projection. In addition, with a ninth-degree polynomial order, a higher value was reached in the confusion matrix overall accuracy. This map showed greater sensitivity within the transition model.

The transition model used for the projection to 2019 reached an accuracy rate of 78.47% (2009–2017) after being executed with the MLP algorithm and under a threshold of 10,000 iterations. An accuracy rate of about 80% is acceptable [65]. Nevertheless, other investigations support using a transition model with an accuracy rate greater than 70% for land cover prediction [38,66]. The confusion matrix, having as a reference parameter the supervised classification for 2019 and its projected data; delivered an overall accuracy of 77.03%, close to the value obtained [1].

The kappa index, analogously to the confusion matrix, provided an overall value of 0.6813. According to [67], it has a moderate concordance; for [68], it holds a substantial precision evaluation; for [69], it is considered a fair-to-good concordance; and for [70], it has a degree of agreement that is close to very good; this interpretive scale is detailed by [41]. Based on [41], the projection is considered acceptable.

Under the same conditions used in the 2019 projections with the maps of the years 2009 and 2017, the land use map for the year 2029 was generated, based on the classified maps of the years 2009 and 2019. Applying the MLP algorithm and under a 10,000 iterations threshold, an accuracy rate of 73.76% was achieved in the transition model of the map projected to 2029. Land cover classified maps for (a) 2009, (b) 2017, and (c) 2019 are presented in Figure 2. Figure 3 shows the projected maps (MLP) for (a) 2019 and (b) 2029.

Map (c) in Figure 2 represents LULC of scenario (1); map (b) in Figure 3 contains LULC of scenario (2). When analyzing the coverage extension, it is evident that the forest area is the most abundant, occupying in the basin 54.81% of its total extension for the year 2019, while on projection for 2029 it occupies 58.72%, so an increase of 3.91% is evident. Another coverage that shows an increase is shrub vegetation, occupying in 2019 an extension of 11.02%, and in the projection for 2029 of 13.71%, denoting an increase of 2.69%. Forest and shrub covers have a projected growth of 6.6%.

Bare soil, grasslands, and crop coverages have presented a reduction of 2.35%, 3.27%, and 0.99% respectively in their projection to 2029, in relation to 2019. Urban extension coverage has not shown changes. These results are presented in Table 1.

3.2. Hydric Recharge Analysis

Multi-year average precipitation obtained for the period under analysis is 1047.8 mm. ETP was equal to 1173.88 mm. The average K_c coefficient of the basin is 0.293. Based on these, the multi-year average recharge estimated for 2019 in the basin is 614.05 mm; for 2029 it is 618.45 mm. This increase is associated with forest and shrub vegetation cover gain. It has also been determined that the highest recharge values are above the 2350 m asl level. This area has mostly forest and shrub vegetation cover. The soil is loam texture mostly, and in some areas, there are also high values of infiltration rates (>16 mm/h). Spatial distribution of hydric recharge results in the basin is presented in Figure 4.

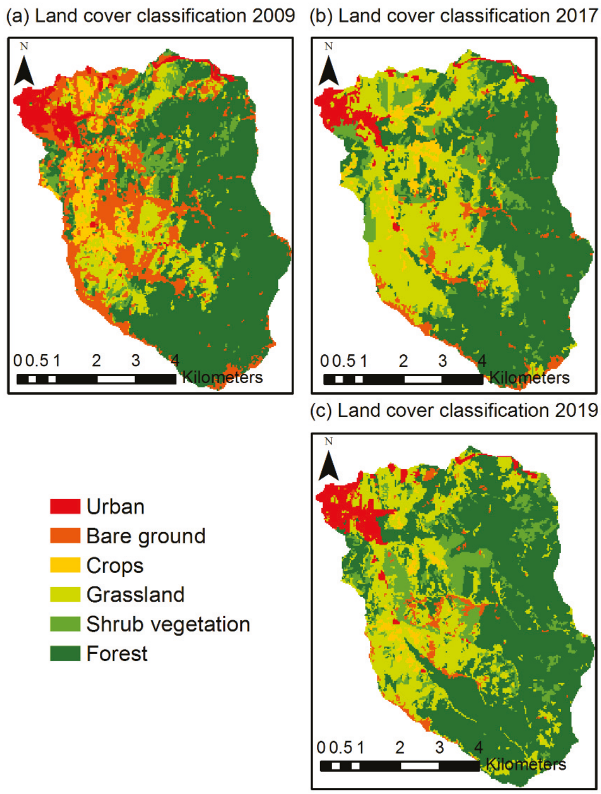

Figure 2. Land cover maps classified for years (**a**) 2009, (**b**) 2017, and (**c**) 2019.

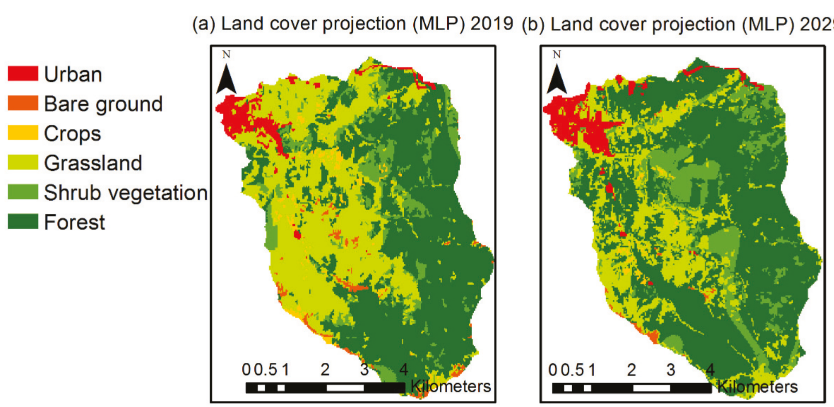

Figure 3. Maps projected with neural networks (MLP) for (**a**) 2019 and (**b**) 2029.

Table 1. Coverage categories extension (%) in relation to 2019 and 2029.

Coverage	2019	2029
Forest	54.81	58.72
Shrub vegetation	11.02	13.71
Grassland	25.72	22.45
Crops	1.63	0.64
Bare soil	2.8	0.45
Urban	4.03	4.03

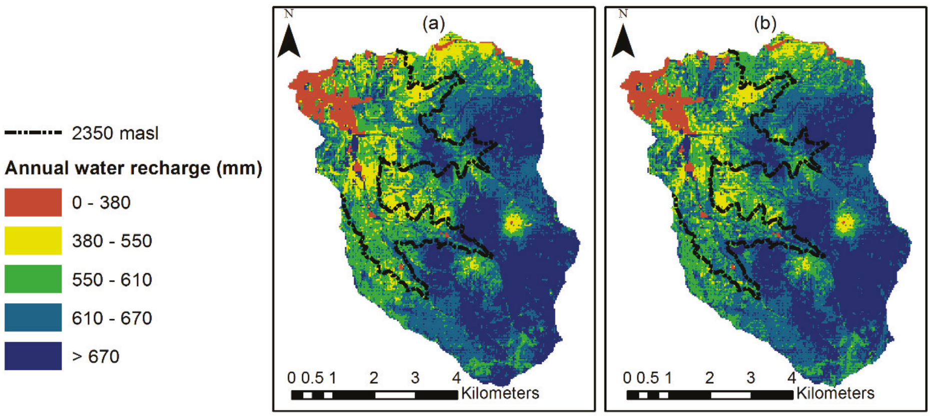

Figure 4. Multi-year average hydric recharge for (**a**) LULC scenario (1) and (**b**) LULC scenario (2).

3.3. Floodplains

A series of maximum precipitation in 24 h of each year was evaluated with different distribution functions using spreadsheets provided by [71]. Precision was estimated through accumulated error, the Nash–Sutcliffe coefficient (NSE), and root mean square error (RMSE). These results are detailed in Table 2.

Table 2. Analyzed distribution functions and their adjustment statistics for the series of multiannual maximum precipitation in 24 h.

Distribution Functions	Accumulated Error	NSE	RSME
Gamma 2 parameters	8.754	0.99	1.21
Pearson Type III	168.38	−3.33	25.77
Exponential	195.86	−4.86	27.16
Nash	10.70	0.98	1.63
Normal	11.33	0.98	2.20
LogNormal	9.19	0.99	1.27
Gumbel	12.42	0.97	1.72

Gamma of 2 parameters was established as the distribution function that best fits the data series. Using this function, the maximum precipitation in 24 h for 3 return periods (Tr) (50, 100, and 500 years) were determined.

Using LULC maps and soil sampling data provided by [27], CN was determined, being 61.66 and 60.96 for the years 2019 and 2029 respectively. There is a projected decrease to the year 2029 due to the increase in shrub and forest vegetation.

Concentration times estimated by the equations provided by Kirpich, Clark, and Temez were 0.53, 1.46, and 2.71 h respectively. Temez was chosen because it adjusts better with the morphological and high Andean conditions of the ZH basin [72].

After calculating mean and standard deviation of peak flow rates obtained with synthetic unit hydrographs, it was determined that the model with results closest to the mean is the Ven Te Chow, which was therefore selected to determine the flood flow rates. Table 3 summarizes obtained values.

Table 3. Return periods, estimated maximum rainfall in 24 h, intensity for a storm time equal to concentration time, and flow rates for 2019 and 2029 coverages.

Tr (Years)	50	100	500
P 24 h (mm)	69.04	73.38	82.72
I Tc (mm/h)	16.24	17.26	19.46
2019 Q (m^3/s)	3.59	5.29	9.92
2029 Q (m^3/s)	3.00	4.55	8.87

The channel was divided into 29 cross sections. The roughness coefficients of the main channel and banks were 0.04 and 0.07 ($s/m^{1/3}$) respectively. Table 4 details a summary of the hydraulic results, the floodplains, and areas susceptible to flooding.

Table 4. Average distance from the center of the channel to floodplain margins along the channel, flooding-susceptible areas, and hydraulic results for each scenario.

Scenario	Tr (Years)	Flooding-Susceptible Areas (ha)	Floodplain Margin (m)	d (m)	v (m/s)
	50	28.80	33.46	1.53	0.41
2019	100	29.47	33.47	1.87	0.45
	500	30.86	35.65	2.05	0.58
	50	28.67	33.42	1.42	0.39
2029	100	29.29	33.45	1.61	0.44
	500	30.65	35.64	1.97	0.56

3.4. Meteorological Forecast

Statistical measures such as MAE, RMSE, and R^2 were determined to verify the model's precision and the chosen parameters. For T average, adjustment statistics are presented in Table 5, and for Pmax average in Table 6. According to the obtained results, forecast Pmax average precision is lower compared to that obtained for T average.

In Figure 5, the ARIMA (3,0,1) model and exponential smoothing models are closely similar, both indicating an 0.11 °C increase in the average temperature for the year 2029.

Table 5. Annual average temperature, models, and adjustment statistics.

Variable	Model	Transformation	R^2	RMSE	MAE
T average	ARIMA (3,0,1)	None	0.44	0.09	0.06
T average	WINTERS	None	0.32	0.08	0.06
T average	HOLT	None	0.30	0.10	0.07

Table 6. Maximum rainfall recorded in 24 h of each month averaged by year, models, and adjustment statistics.

Variable	Model	Transformation	R^2	RMSE	MAE
Pmax average	ARIMA (1,0,0)	Natural logarithm	0.12	3.31	2.63
Pmax average	WINTERS	None	0.06	2.93	2.67
Pmax average	HOLT	None	0.02	3.46	2.91

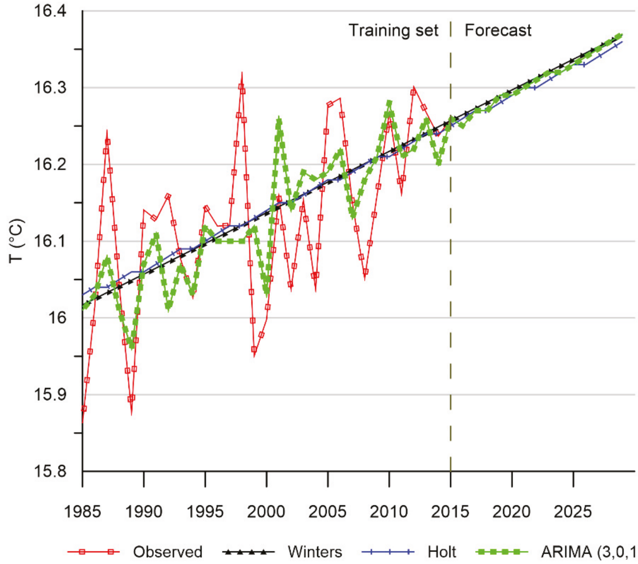

Figure 5. Annual average temperature forecast using ARIMA and exponential smoothing models.

In Figure 6, models keep similarities in forecasts, but given the stochastic nature of rainfall [73], they do not reach a high adjustment value. Models show an increasing trend, according to the ARIMA model (1,0,0), toward an increase of 15.63% in the year 2029, taking the year 2015 as a reference. In contrast, other researchers point out that in high Andean zones of Ecuador there is an incremental tendency in annual rainfall [74].

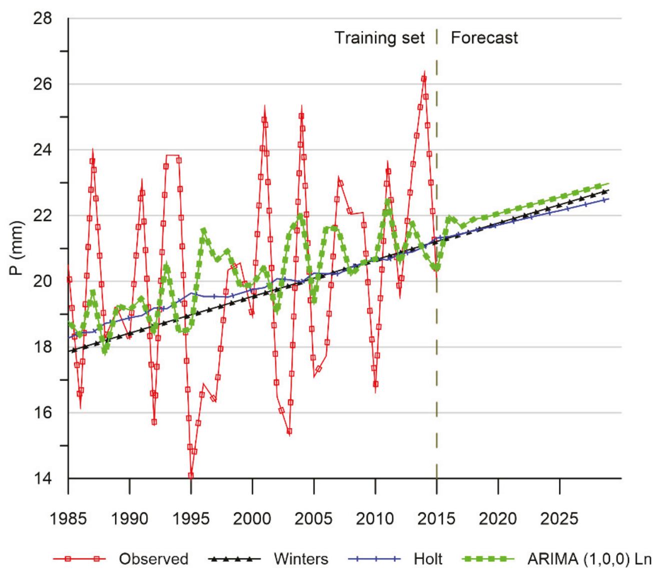

Figure 6. Maximum rainfall recorded in 24 h of each month averaged per year, forecasted with ARIMA and exponential smoothing models.

The temperature increase in Figure 5 is related to the increase in precipitation in Figure 6. Temperature peaks precede the precipitation peaks and when the precipitation presents higher values the temperature shows a decrease with a convex curve. In the future, as temperature increases, the peaks of precipitation would also increase, resulting in storms of greater intensity and therefore an increased risk of extreme hydrological events such as floods.

In Figures 5 and 6, the forecast final values are close to each other. After the training set, those have an upward growth, following the series' central tendency. This is because the ARIMA model and the exponential smoothing models are adjusting to series that have no periodicity.

3.5. Basin Hydrological Response

Simulated hydrographs show a seasonality associated with 24 h precipitation. The 2019 scenario reaches higher values in peak flows and lower values during dry season. The scenario for 2029 shows better flow regulation by obtaining lower values at peak flows and higher in the dry season in relation to the 2019 scenario. The hydrological response of the basin is shown in Figure 7.

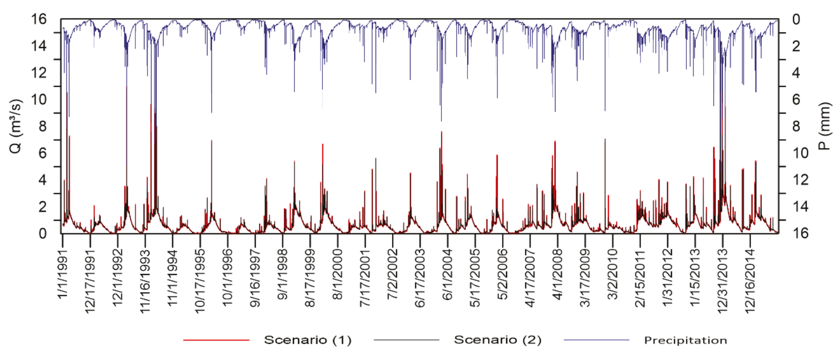

Figure 7. 24 h precipitation and simulated flows at the basin exit for LULC scenarios (1) and (2).

Surface runoff (annual average) decreased by 1.37%, due to the increase in forest and shrub vegetation areas and the decrease in agricultural cover. The flow duration curves (FDC) (Figure 8) show that, for the 2019 coverage scenario, there is a flow of 0.3228 m^3/s with a 90% probability of exceedance, while for the 2029 scenario it is 0.328 m^3/s. The flow regime with a 90% probability of exceedance is 1.85% (7.72 L/s) higher for the 2029 than it is for the 2019. This trend has found up to a 1% probability of exceedance, reaching an increase of 1.05%.

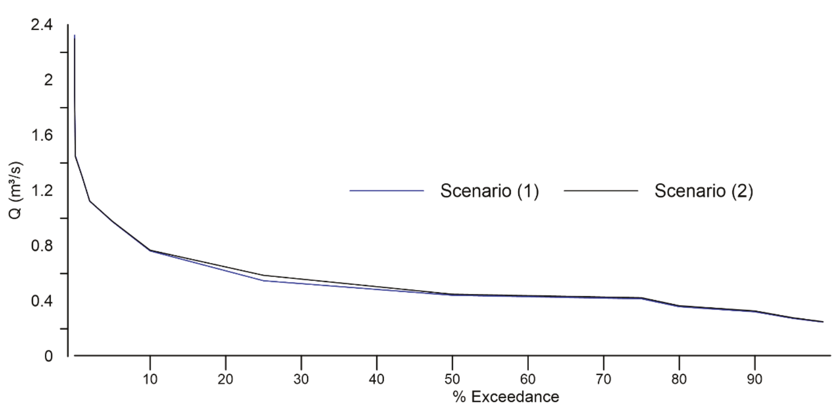

Figure 8. FDC for LULC scenarios (1) and (2).

On the other hand, with a probability of exceedance of 0.01%, the 2019 coverage scenario has a flow of 2323 m^3/s. For the 2029 scenario, it is 2298 m^3/s; that is, there is a decrease of 1.07%, a trend that is maintained for exceedance probabilities of less than 1%. These results are related to the behavior of extreme flood events flows analyzed in Section 4.3.

4. Discussion

4.1. LULC and LUCC Analysis

Land use practices such as agriculture and livestock have been limited in recent years mainly due to municipal intervention policies for the preservation of water sources. Actions taken have allowed a forest recovery, which is evidenced in the projected increase in its coverage. Additionally, [75] indicates that the population of the area will decrease at a rate greater than 1.56%, which makes sense with the non-existent growth of urban cover.

4.2. Hydric Recharge Analysis

Forest and shrub vegetation cover gain increases hydric recharge rate since it supposes a greater fraction of rain that is intercepted by vegetation. Areas where this increase is greater are located above 2350 m asl, which is also the level where a catchwater is located.

All areas related to water supply are protected by a mercantile escrow subscribed to by local government and the Regional Water Fund FORAGUA. One of FORAGUA's main activities is the purchase of lands that are located within zones identified as water recharge zones (WRA). Most of the purchased land was declared as a municipal reserve. In those zones, any exploitation is forbidden [23]. That is why forest species have the potential to extend their borders and improve the water regulation in the basin.

4.3. Floodplains Analysis

According to Table 4 and Figure 9, floodplain margins and flooding-susceptible areas have a limited increase for return periods greater than 50 years. In addition, a reduction is expected by 2029. A remarkable number of rural buildings, agricultural land, and orchards are located on the riverside within the margin of the floodplains. This problem occurs because of fertility and ease of access to the areas.

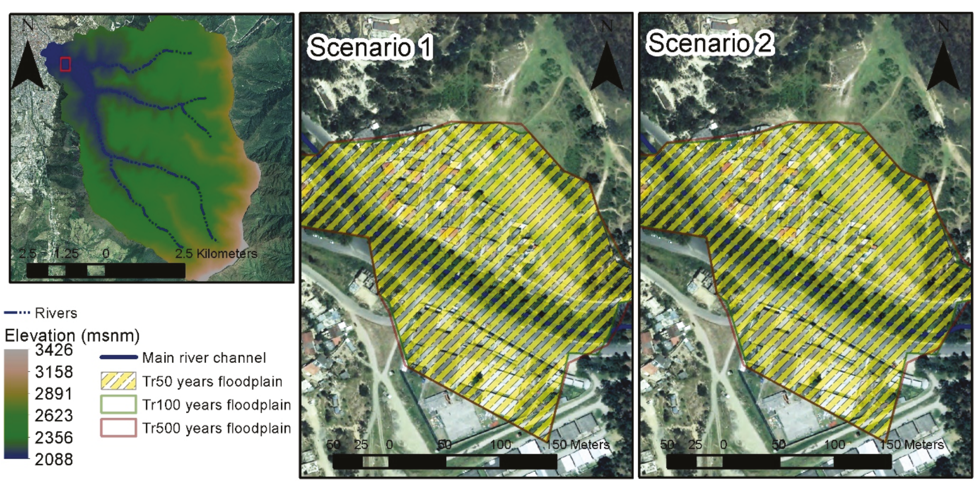

Figure 9. Floodplains for each return period and LULC scenarios in an area near to basin exit.

4.4. Meteorological Forecast Analysis

Average temperature increments indicate an increase in terrestrial radiation (reflected solar) due to the presence of clouds (mainly before the first hours of radiation) and greenhouse gases (GHG) [76,77].

Adaptations in the basin, due to climate change, should be channeled around the increase in average temperature and the increase in high intensity rainfall. Being temperature linked to atmospheric pressure and amount of water vapor in the air, as it increases, the air rises by convection and gets colder, producing cloudiness, and eventually precipitation [76,77]. As there is an increasing trend in maximum precipitation, there is a probable increase in peak flow rates of flash floods.

Forecasts show a tendency to increase in maximum rainfall in 24 h, so a scenario considering its possible effects is appropriate to achieve assertive management of hydrological risks [22].

Precipitation forecasts do not provide reliable estimations of future patterns at the local scale. However, they point to an increasing trend. [22] also reports uncertainties in the precipitation forecast, noting that these are only worthy when the impacts of climate change are considered in their scenarios.

4.5. Basin Hydrological Response Analysis

FDC comparison shows an improvement on the water regulation capacity. Forest and shrub vegetation cover increments influenced the surface runoff and water recharge, and therefore the flow regulation. The greatest contribution to base flow was caused by lateral and underground flows. According to the model, the annual average of both contributions to the base flow in the 2019 scenario was 455.35 mm, while for the 2029 scenario it was 459.67 mm. These results support the premise that a mainly wooded area limits the source material of surface runoff, and therefore favors water recharge [78]. Forest and shrub vegetation trap sediment and delay runoff between adjacent zones, facilitating percolation and drainage of water through the soil, increasing base flow [1,78].

4.6. Actual Context of the ZH Basin and the Need for IWRM

These particular models comply with the initial stage of IWRM diagnosis. In a complementary investigation, these results are expected to be used in a prospective study of future scenarios and to develop a strategic plan to achieve a desired future, particularly by developing territorial prospective and implementation strategy stages [3]. A detailed description of each model used is given in Table S1 in Supplementary Materials.

In addition, the management of this particular basin is of vital importance for Loja city due to the fact that it provides about 50% of the water for human consumption [30] not considering its agricultural use, so, there is demographic pressure around the hydric resource [79]. The basin has been intervened with in terms of conservation, with highly restrictive regulations related to human activities. The local government has also bought lands closed to catchments to protect water supply, however, wealthy owners still retain some properties focused on areas in the upper part of the basin [80]; therefore, the conditions of change of use and land cover are atypical and deserve to be studied, in addition to their effect on the different natural physical processes associated with water. The meteorological forecast was developed in order to contextualize the increase in temperature and extreme rainfall and to raise the need for adaptation measures to climate change.

5. Conclusions

Forest and shrub covers show an increase for the 2029 scenario, which has a strong influence on natural physical processes in the basin. Hydric recharge suggests an increase in 2029, with the areas that favor it mostly located above 2350 m asl. The drinking water catchment points above this altitude, so it must be ensured that agricultural practices be carried out below this level in the basin.

Peak flow rates of flash floods show a reduction for the future LULC scenario. Flood margins do not show a significant decrease; however, on average they are located 36 m from the course of the river, so agricultural practices and human settlements should be limited to outside that margin to decrease their vulnerability.

Forecasts made up with the three models considered (Holt, Winters, and ARIMA) show an increase in average temperature and extreme rainfall (even with the associated uncertainties). On this issue, management strategies must deal with unpredictability and a correct capacity to respond to possible conditions of climate change.

Considering that the flow regime with a 90% probability of exceedance is greater for scenario (2) than for scenario (1), it is evident that basin recovery is due to an improvement on flow regulation related to increase of forest and shrub vegetation cover.

Intervention strategies in Andean basins can be supported in prospective studies using these key system variables focused on the integrated management of water resources.

Supplementary Materials: The following is available online at https://www.mdpi.com/article/10.3390/land10050513/s1. Table S1: Description of each methodology subsection, data, and models used.

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Communication

Improving Best Management Practice Decisions in Mixed Land Use and/or Municipal Watersheds: Should Approaches Be Standardized?

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Abstract: Best management practices (BMP) are defined in the United States Clean Water Act (CWA) as practices or measures that have been demonstrated to be successful in protecting a given water resource from nonpoint source pollution. Unfortunately, the greatest majority of BMPs remain unvalidated in terms of demonstrations of success. Further, there is not a broadly accepted or standardized process of BMP implementation and monitoring methods. Conceivably, if standardized BMP validations were a possibility, practices would be much more transferrable, comparable, and prescriptive. The purpose of this brief communication is to present a generalized yet integrated and customizable BMP decision-making process to encourage decision makers to more deliberately work towards the establishment of standardized approaches to BMP monitoring and validation in mixed-use and/or municipal watersheds. Decision-making processes and challenges to BMP implementation and monitoring are presented that should be considered to advance the practice(s) of BMP implementation. Acceptance of standard approaches may result in more organized and transferrable BMP implementation policies and increased confidence in the responsible use of taxpayer dollars through broad acceptance of methods that yield predictable and replicable results.

Keywords: best management practices; watershed management; experimental watershed study design; municipal watershed; adaptive management

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1. Introduction

Pollution from diffuse sources is most often driven by meteorological events (i.e., precipitation) and alterations to stormwater runoff processes [1,2]. The latter, termed hydrologic modification can increase or decrease diffuse pollution loads, the extents of which are poorly understood and difficult to mitigate based on research from other locations. The challenge of transferability necessitates the need to monitor and subsequently quantify stormwater runoff processes, pollutant transporting mechanism(s), and the various pathways contaminants may travel from source areas to receiving water bodies in most if not all contemporary municipal and/or mixed land use watersheds. This is important because with limited information for local watersheds, stormwater managers struggle to predict the effect of local ordinances on local receiving water bodies water quality. Given the challenges of predicting climate and landscape interactions, it is not surprising that meeting water quality goals such as Total Maximum Daily loads (TMDLs) is a challenge, particularly in rapidly urbanizing watersheds. Certainly, estimating a TMDL for water quality is laudable goal. However, translating pollutant loading to specific land uses, and subsequent development-related mitigation strategies, is a difficult task without understanding water and pollutant transport at multiple locations in a watershed [3–5].

There is thus an ongoing need for cost-sensitive and effective methods of monitoring best management practices (BMPs) in contemporary watersheds that are transferrable and adaptable to local watershed needs. This includes the need for standardized methods to make BMP decisions in the most effective locations using accepted methods of monitoring that thereby meaningfully advance BMP decision making, efficacy and cost reductions. For example, the experimental watershed study design (EWSD) provides an overarching and customizable monitoring structure that has been shown to successfully quantitatively characterize the effects of land use practices on receiving waters in mixed land use settings for well over a century [6–10]. Nested EWSDs divide a larger watershed into a series of sub-catchments to investigate the influence of land use practices on environmental variables of interest [4,8,11]. This monitoring design is important because sub-catchment delineation isolates varying land use practices, BMPs, and hydrologic characteristics [4]. The monitoring design enables the identification of the cumulative effects of land use practices on response variables of interest. It does this through the quantification of the influencing processes observed at the sub-catchment scale thereby improving BMP decision-making efficacy based on validation. The purpose of this communication is to present a process, and by implication the need, for more deliberate integration of BMP decision implementation and validation processes and to encourage consideration of a standardized approach that may significantly advance validation and transferability of BMPs in complex mixed-use municipal watersheds. The reader is referred to the many supporting citations (and citations therein) for further understanding of the state of the science.

2. The BMP Decision-Making Process and the Critical Source Area

BMPs are generally categorized based on the intended pollutant or pollutants a given practice will mitigate. For example, stormwater management BMPs are control measures that are intended to mitigate changes to both the quantity and quality of urban runoff caused by land use impacts [11]. Stormwater BMPs are typically designed to reduce stormwater volume, peak flows, and/or nonpoint source pollution through independent or combined evapotranspiration, infiltration, detention, and filtration or biological and chemical processes [12]. BMPs can improve receiving-water quality by extending the duration of outflows in comparison to inflow duration (known as hydrograph extension), which dilutes the stormwater discharged into a larger volume of upstream flow [13]. To at least in part address this challenge, the United States Environmental Protection Agency (USEPA) recommends that effective application of agricultural, urban, and other nonpoint source (NPS) BMPs should include the identification of critical source areas (CSAs), or areas that are particularly susceptible to flow and pollutant sink and source processes, and that are therefore important to the BMP implementation planning processes and short and long-term BMP efficacy [14]. BMP implementation in tandem with other practices in CSAs is important to achieve the goals often delineated in Watershed Management Plans (WMPs) or Total Maximum Daily Loads (TMDLs). The outcomes of these are intended to result in achieving water quality and quantity goals and objectives, including (but not limited to) the restoration and protection of the designated beneficial uses of source waters [14]. The USEPA approach to identifying CSAs is a results-based methodology designed for selecting both appropriate BMPs and BMP systems and identifying the necessary management strategies to support or promote BMP implementation in critical locations. The methodology includes (in brief) (a) determining restoration/protection priorities, (b) identifying the connections between potential source and transport pathways, (c) estimating the relative contribution from source and transport pathways, (d) describing the expectation of CSAs and BMP performance including implementation opportunities, (e) focusing CSAs and associated BMPs and BMP systems where they will be most effective, and (f) monitoring progress and adjusting as needed through an adaptive management approach [14]. The USEPA further recommends a multi-disciplinary ecosystem approach for identifying CSAs and selecting BMPs, BMP systems, or other management measures to take advantage of the knowledge, data, and expertise of all stakeholders [14]. The importance of stakeholder engagement (and stakeholder engagement theory) is particularly relevant given that fairness and reciprocity of decision making should be among the primary objectives to encourage greater value in outcomes [15,16]. It is therefore important to encourage a process that includes many different actors including (but not limited to) government authorities, local communities, environmentalists, consumer defense organizations, competitors, special interest groups, and the media [17].

The process of ecosystem restoration planning and implementation can be aided by the use of conceptual frameworks, which typically include a conceptual diagram illustrating relationships between key drivers, stressors, ecological impacts, and management responses [18,19]. In addition to visualizing relationships between known or suspected stressors and ecological impacts, such diagrams can help ensure appropriate management actions are being taken to address key problems, reduce impacts, and subsequently lead to restoration. An important component regarding the identification of CSAs is determining priorities that will address recognized problems/concerns relative to water quality management plan goals and objectives (Figure 1). Information used to target priority areas of the greatest concern includes water quality data, flow data, biological assessments, and habitat evaluations [14]. Following priority determination, the methodology helps identify connections linking problems to potential sources. This approach facilitates delineation of potential source areas through the utilization of mapping tools designed to aid in the assessment of key factors such as land use information, management measures and practices (e.g., livestock rearing or urbanization).

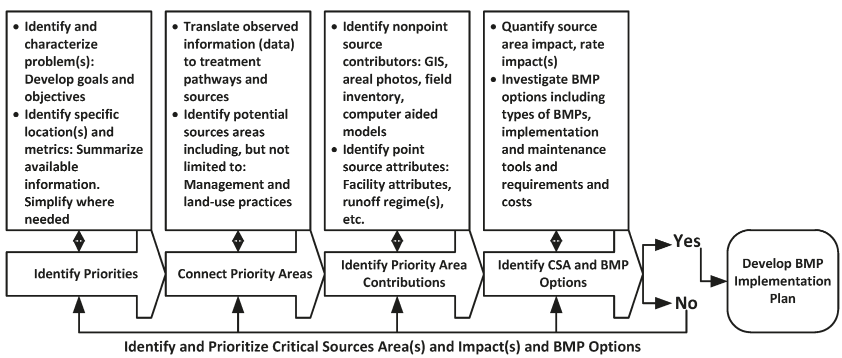

Figure 1. Process for integrating necessary information to develop critical source area (CSA) assessments and prioritize best management practice (BMP) implementation. Simplified after [14].

The goal of the process presented in Figure 1 is to reduce the number of potential source areas to those locations where BMP implementation will be most effective in achieving water quality goals. Ideally, this would be a standardized practice for all BMP implementation decision processes. The estimates used in this step can vary from narrative descriptors (e.g., high, medium, low) resulting from aerial photo analysis or field inventories to quantitative values developed from desktop screening tools or models. Following estimation of relative contributions, CSAs and BMP opportunities are targeted with the goal of ensuring that implementation resources are utilized on suitable management practices and are directed to areas that contribute disproportionally to problems and concerns [14]. Source areas are rated based on detailed survey data analysis. The process may be iterative given that choices and decisions are not always apparent, often requiring additional data collection, compiling or reexamining information used in preceding steps [14]. Finally, monitoring implemented BMPs for efficacy will produce the information required to make improvements to an adaptive management framework.

3. BMP Monitoring

Many observational studies and modeled scenarios have been utilized to evaluate BMP efficacy, particularly BMPs aimed at improving water quality [1,20–25]. For example, studies assessing the impacts of agricultural BMPs on physiochemical conditions in streams have produced a wide range of values for reductions in nutrients and sediments [24,26–29]. Other study parameters have included physical habitat, geomorphic characteristics, chemical metrics, temperature, and other variables [30]. Habitat (e.g., substrate, bank, and riparian condition) and stream geomorphology (e.g., channel shape and width) have also been shown to be intermediate-term response indicators of incremental change during the time lag between improvement in chemistry and improvement in biological health [31–33]. It must be acknowledged that the improvement of aquatic ecosystems following BMP implementation is subject to the response of other functional processes as well, including (but not limited to) hydrology, hydraulic processes, geomorphology, and physiochemistry [34,35].

Biological community assessments can be used to monitor the long-term and large-scale outcomes of BMPs [30]. Many organisms are typically present in streams over longer periods of time relative to physiochemical components and can therefore be used to determine the stability of the ecosystem response to BMPs [36,37]. Additionally, the simultaneous assessment of integrated biological communities (e.g., algae, fish, and macroinvertebrates) can provide a more complete assessment of stressors and impacts on several temporal and spatial scales [38,39]. For example, diatoms (Bacillariophyta) can be exceptional indicators of BMP effectiveness as they are sensitive to specific levels of nutrient concentrations, conductivity, and pH [30]. Diatoms also exhibit rapid response times to BMPs, making them well-suited to indicate short-term changes, at a scale of weeks or months [40–42]. Macroinvertebrates are less susceptible to nutrient enrichment than diatoms [43]; however, they can be utilized to study watershed-scale eutrophication, the impacts of land use change, and monitor local-scale habitat health, temperature, streamflow, and oxygen levels over the medium- to long-term (5–20+ years) [30]. Consequently, monitoring macroinvertebrates over numerous years, accounting for interannual variation, can be useful for determining the stability of the ecosystem response to BMP implementation [44,45].

Model development using data gathered from observational studies of water chemistry or biotic communities and the professional consensus of experts facilitate the ability to predict the potential or expected effects of BMPs [30]. Indeed, models are often used for the development of decision-making tools to help managers and landowners implement BMPs that have the greatest possible benefit to water quality [46–49]. These tools commonly include assumptions regarding BMP efficacy in reducing constituent concentrations (e.g., sediment and nutrients) [30]. For example, efficiency estimates, ranges of percentages in nutrient and sediment reduction expected from different BMPs, are commonly developed for model inputs from a range of observational water quality studies and best professional judgement [25,31,50]. Efficiency estimates have been implemented in conservation practices utilized in numerous models implemented in the US Mid-Atlantic region including the Chesapeake Bay Model [24,51–53], MapSheds and PRedICT [30]. For example, in the Chesapeake Bay Watershed it is anticipated that total phosphorus (TP) reductions would be roughly equivalent to 75% of total suspended sediment (TSS) reductions, given the assumption that 75% of TP is bound to sediment and not dissolved [24,54].

4. Measuring Effects of BMPs

A review of 94 investigations indicated that only 60% of management practices showed clear evidence of reductions in nutrient concentrations [55]. The authors noted a lack of consistency regarding the study designs, BMP type, or treatment area. Modeling-based studies more consistently predicted water quality improvement following BMP implementation. However, that was presumably due to controlled model routines [55]. The inherent subjectivity of modeling can therefore create problems regarding data comparison, given observational and modeled results are often not interchangeable [30]. The lack of consistent sampling and indicators used in different BMPs also complicates the comparison of results and the ability to draw conclusions [30].

Implemented BMPs have also resulted in inconsistent validation results, with both study design and spatial and temporal scale of monitoring influencing inconclusive outcomes and resultant lack of transferability [30], a problem that could be addressed with standardized monitoring protocols [4]. Generally, positive water quality outcomes were reported for larger scales in watersheds comprising an aggregation of combinations of various BMPs [26,56–61]. Evidence of the success of BMPs includes reduced eutrophication and algal growth, and hypoxic or anoxic conditions decreasing in area and duration in large receiving waters [30,61,62]. The success of BMPs may also be localized; for example, the effects of BMPs for livestock grazing and activities within streams on small scales can be difficult to detect farther downstream [62,63]. For example, Thomas (2002) showed improved Index of Biological Integrity (IBI) scores at the site of BMP implementation, although not downstream, in a 140 ha watershed in the Altamaha River basin. Conversely, BMP impacts may only be detectable on larger scales. For example, Line et al. (2000) did not observe total suspended solid (TSS) reductions at the site level but observed a cumulative reduction at the watershed scale in North Carolina. Notably, the results of BMPs are also impacted by the period over which they are studied. Studies that take place over long periods (5–20 years), including both small and large spatial extents, are typically more representative of the effects of BMPs [20,64].

Several factors can contribute to the lack of consistency in the measurable effects of BMPs. For example, detecting changes in streams can be complicated by the intended scale of impact, the lag time for ecosystem response, weather events, and local conditions [30]. A review of farm BMPs in 2019 showed that BMP implementation is often opportunistic, involving widely dispersed implementations throughout large geographic regions focusing on reaching desired effects at the local scale [30]. However, other recent studies demonstrated that merely increasing the number of implementation sites for BMPs may not optimize investment towards improved water quality at local or watershed scales; rather, targeting specific geographic locations and preferentially investing in specific BMPs is expected to result in greater overall impact [15,48,65–68]. This is of particular relevance given that planning BMPs should occur at a watershed level to ensure upstream impacts that place stress on lower reaches can be fully accounted for and addressed [14,47].

5. Monitoring Mixed-Use and Municipal Watersheds: A Standardized Approach

The above challenges can be contended with using targeted monitoring programs at the reach to the watershed scale [30]. The experimental watershed study design (EWSD) can serve this purpose [4]. The EWSD includes multiple sites monitoring the same indices at the same time. This in-situ monitoring approach has the potential to enhance understanding of when BMPs are having their intended effect, and alternatively when they are not achieving a significant or measurable reduction in inputs at stream reach or watershed scales [45,69,70]. A review in 2019 of 277 studies showed that baseline (prior to implementation) data should be collected (when possible) to understand pretreatment conditions and better predict BMP success [30]. The long-term multi-spatial resolution sampling characteristic of the EWSD study design is ideal to monitor water quality metrics both prior to and following the implementation of BMPs and can greatly increase the confidence landowners and water quality managers have in the efficacy of implemented BMPs. Figure 2 shows examples of typical EWSDs including paired and nested (Figure 2A,B), modelled after [71], the nested-scale design, modelled after [4], and the nested-scale and paired design, modelled after [72]. These designs are useful for municipal and/or mixed land use watersheds because they can be applied to watersheds that are currently in a dynamic multiple-use state. The designs can therefore be considered in-situ designs that can be used at any time, at any stage of design and BMP implementation. What is important is to simply start monitoring, and continue monitoring so that before and after periods are captured pre- and post-BMP implementation [4]. Notably, these designs also increase monitoring efficacy due to multiple monitoring sites and can also ensure that limited taxpayer funds spent on BMPs are used effectively. This is important given that in the United States alone, funding invested in BMPs can constitute substantial sums. For example in the period of approximately 2005 to 2015, an estimated USD 30 billion was invested to fund federal conservation programs and protect public health and the environment [73].

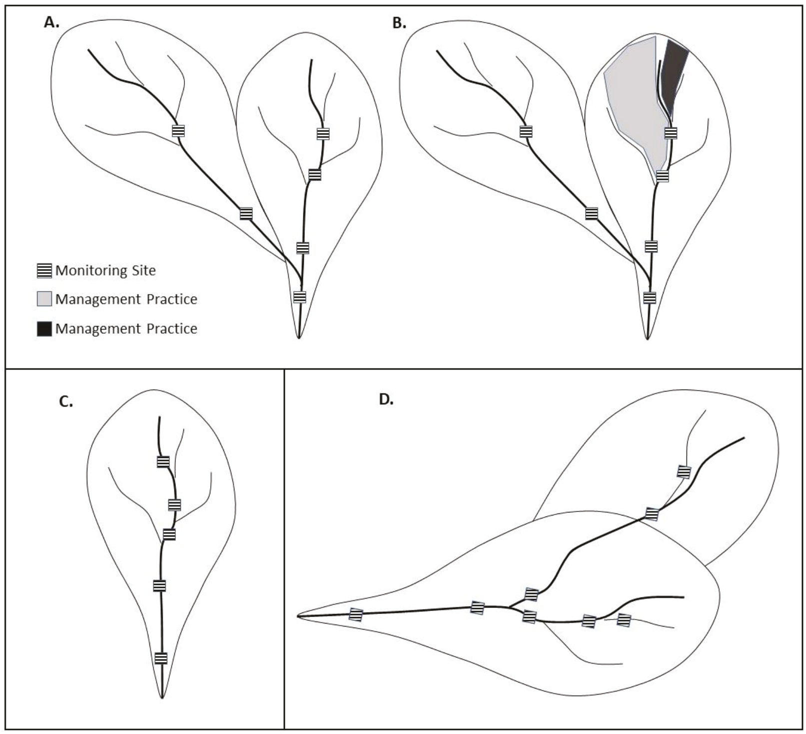

Figure 2. Nested figures include idealized catchments with examples of (**A**,**B**) paired and nested EWSD with (**A**), control (left) and treatment (right) catchments, and monitoring during a calibration period, (**B**) control (left) and treatment (right) catchments, and monitoring after changes (arbitrary) in management practices (shaded area in B), modelled after [71], (**C**) the nested scale design, modelled after [4], and (**D**), the scale-nested and paired design, modelled after [72,74]. These can be considered in-situ designs as there may be land use practices occurring (pre-existing) before, during and after subsequent BMP implementation. Monitoring site locations shown are arbitrary and must be user-defined.

The EWSD monitoring approach is an increasingly used, globally accepted, method to monitor hydrologic and water quality processes, identify CSAs and most impactful locations for BMPs in municipal watersheds. The EWSD has been shown to quantitatively characterize hydrologic and water quality conditions and changes effectively. It also is effective at addressing both site-specific management questions, BMP efficacy, and assisting model development, validation, and calibration [4,69–72,74–78]. Historically, the method may have been infeasible for many municipalities due to funding constraints and the historic high costs of instrumentation, labor, the often time-consuming process of data collection, as well as the expertise required for data analyses and interpretation of results [4,6,8,75]. While these perceptions may persist, recent reduced-cost technologies and the inherent long-term fiscal advantages of the experimental watershed study design far outweigh the potential disadvantages. Importantly, if preemptive, the design can be used to collect pre-treatment information (Figure 2). This is important given that pre-existing (antecedent) conditions prior to BMP implementation are most often infeasible and completely missing, but critical for BMP efficacy assessments. Unfortunately, without this information it is nearly impossible to justify changes in approach(es) for future implementations.

To advance and/or consider standardization of the BMP process, there may be a need to couple the EWSD with a process that includes a logical sequence of steps to satisfy project objectives before, during, and after implementation. There are many such plans adapted by managers and policy makers including that used by the Natural Resource Conservation Service (NRCS) [79], recreated and simplified in Figure 3. Planning steps are not always linear but may be cycled through iteratively to develop the best set of alternative solutions to a given problem, and ultimately select and implement a certain set of practices. For this example (Figure 3), the steps generally include the following. (1) Identify problems and opportunities: What characteristics should be changed? Is the noted condition actually a problem? (2) Determine overall goals and specific objectives: What are the desired physical, chemical, and biological outcomes? (3) Inventory resources: Understand the dominant physical processes, and impact variables of interest. (4) Assess assembled information and decide what processes most influence the desired condition. (5) Determine which processes can be changed (if any). (6) Assess alternatives. (7) Decide on courses of action. (8) Implement the plan. (9) Evaluate outcomes to assess performance and revise practices. Other methods include the integrated watershed management (IWM) approach that includes management planning to improve areas of concern including (but not limited to) water availability, increased food production, improved livelihoods, and sustainability of mixed land use watersheds [80]. In many locations (globally), the IWM approach has also been used to address gender issues and the generation of social capital and economic benefits for rural populations [80,81]. This approach, therefore, facilitates the protection of critical water resources while simultaneously addressing issues such as the current and future impacts of population and/or population and land use growth and climate change [4]. Finally, outcomes of these efforts can be improved in the long-term through effective collaborative adaptive management (CAM; or derivative) efforts [4,16–18].

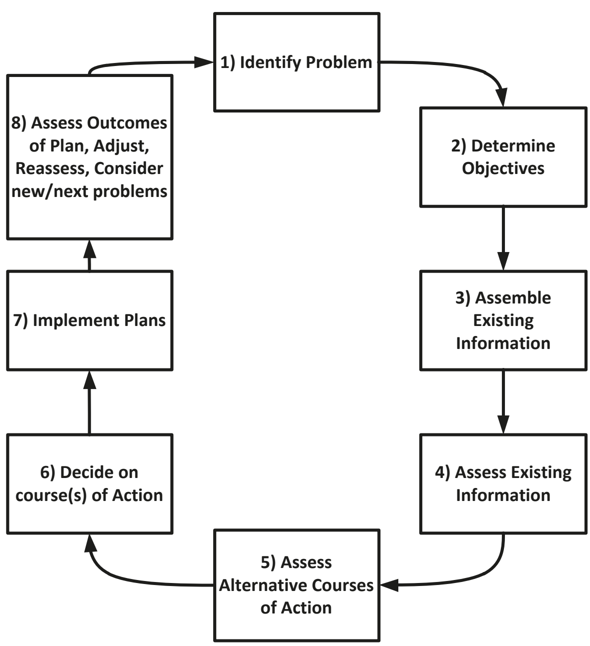

Figure 3. Example of a nine-step planning process to develop and implement plans that protect, conserve, and enhance natural resources within a social and economic construct, recreated from [79].

6. Synthesis and Conclusions

The processes described and diagrammed above imply an iterative approach. The properly prioritized identification of CSA and BMP implementation will help prioritize the most sensitive CSAs and the most effective locations for BMPs. The in-tandem EWSD approach can facilitate the pre-implementation assessment, monitoring following implementation, and provide critical information necessary to determine the short- and long-term quantitative efficacy of implemented BMPs [4,67–71,74,75]. The coupled EWSD and logical flowpath (steps) approach, from identifying the problem to BMP implementation and validation, can lead to greater confidence and stakeholder buy-in regarding BMP efficacy.

The integration of approaches outlined herein facilitates the identification and quantification of factors contributing to impairment, and provides information needed to target mechanistic drivers, both natural and anthropogenic, of hydrologic and/or water quality alteration. Efficiency in planning and monitoring pre- and post- BMP implementation can quantitatively chronicle the compounding impacts of land use practices, hydroclimatic variability, and physical watershed characteristics on water quantity and quality regimes. There is a need for studies focused on the lifecycle of these processes, including the econometric benefits (or detriments). Ultimately, the ability to supply more scientific and socioeconomic information to stakeholders ensures buy-in and support for watershed best practices leading to improved long-term watershed management decision-making.

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Spatial Pattern of Functional Urban Land Conversion and Expansion under Rapid Urbanization: A Case Study of Changchun, China

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Abstract: As populations continue to be concentrated in cities, the world will become entirely urbanized, and urban space is undergoing a drastic evolution. Understanding the spatial pattern of conversion and expansion of functional urban land, in the context of rapid urbanization, helps us to grasp the trajectories of urban spatial evolution in greater depth from a theoretical and practical level. Using the ESRI ArcGIS 9.3 software platform, methods, such as overlay analysis, transition matrix, and kernel density estimation, were used in order to analyze the spatiotemporal characteristics of different types of functional urban land conversion and expansion in the central city of Changchun. The results show that different types of functional urban land were often expanded and replaced, and the urban spatial structure was constantly evolving. The conversion and expansion of functional urban land show similar characteristics to concentric zone and sector modes and show dynamic changes in different concentric circles and directions at different periods. Our method can accurately identify the different types of functional urban land, and also explore the evolutionary trajectory of urban spatial structure. This study will help to coordinate the development of different functional urban spaces and to optimize the urban spatial structure in the future.

Keywords: functional urban land; urban space; urban land use/cover change; urbanization; Changchun

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1. Introduction

As the urban population continues to increase, cities have always been the focus of scholars and policy makers [1]. More than 50% of the world's population is currently concentrated in urban areas [2] and it is estimated that this will reach 70% by the year 2050 [3]. With the rapid increase in urban population, urban space is constantly expanding [4]. Urban–rural population migration [5], cross-regional population mobility [6], and bidirectional urban flows [7], are considered to be the main driving forces of the increase in the urban population. Changes in the urban land use/cover and their environmental consequences, such as the sustainable development of urban space [8] and the spatial mode of urban land change [9], have become important topics in the field of urban land research. In the context of rapid urbanization, the phenomenon of conversion between different types of functional urban land often occurs in urban built-up areas [10]. However, scholars have not paid enough attention to the phenomenon. Although big data, such as point-of-interest (POI) and vehicle trajectories, have been used to identify functional urban areas, it is difficult to accurately classify the different types of urban land [11–13]. Relying on the urban land use maps of the past few years and other auxiliary data, we have obtained a detailed classification of urban construction land based on different uses, which is helpful for analyzing spatial patterns of functional urban land conversion and expansion.

Unlike urban land conversion, the expansion of urban land has become a relatively common phenomenon worldwide and has attracted widespread research attention [14]. Remote sensing and geographic information systems (GIS) facilitate the study of urban land expansion [15,16]. Xiao et al. (2006) used Landsat images and the annual urban growth rate to analyze land use change and urban spatial expansion in Shijiazhuang [17]. López et al. (2001) analyzed and predicted land use change on the fringes of a Mexican city [18]. Polimeni (2005) analyzed the replacement of agricultural land by residential land caused by the expansion of urban land in the Hudson River Valley [19]. The expansion of urban land occupies a large part of non-urban land [20], especially in the metropolitan areas of Southeast Asia [21]. For example, a large area of high-quality farmland has been replaced by urban land in Beijing [22]. In the above studies, the scholars have analyzed the expansion of urban land from a regional perspective. They paid attention to the overall expansion of urban land and did not subdivide the types of urban land. Therefore, our perspective is different from theirs as we are concerned about different types of urban land in the city.

Regarding the study of urban land within a city, scholars have focused on the identification of functional urban areas or land. Big data are often used to identify functional urban space and to analyze the organization of functional urban spaces [23–26]. Tian et al. (2010) used POI data to divide the functional urban space of Beijing and pointed out that Beijing belongs to an urban spatial structure similar to that of the concentric zone mode [24]. Chen et al. (2020) compared the similarities and differences in the spatial organization of the urban functions in 25 Chinese cities with help of POI data [25]. In contrast to Tian et al.'s conclusions, Liu et al. (2021) used carpooling big data to identify the regional centers and highlighted the polycentric spatial structure of Beijing [26]. In addition, the redevelopment of a certain type of urban land occasionally appears in the existing literature. Under the influence of industrial decentralization, industrial land is constantly being replaced by other urban construction lands [27–31]. Charney (2015) analyzed the conversion between office land and residential land in the central urban area of Tel Aviv [32]. There are many other types of land use in cities, but these have not received enough attention.

The opening to the world in 1978 was the starting point for the rapid development of Chinese urbanization. After 40 years of development, the urbanization rate increased to 59.78% in 2018, which is an increase of 41.68% from 1978 [33]. This rapid urbanization has caused a fast expansion of urban space in most Chinese cities, especially in provincial capitals and cities in east China. From 2003 to 2015, urban development land increased by 22,612.2 km^2 [34]. However, the rapid expansion of urban space has not automatically led to high-quality urban construction or stable use of urban land. The conversion of urban land use continued to occur in urban built-up areas [35,36]. According to William Alonso's bid-rent theory, the price of commercial land is the highest, the price of industrial land is the lowest, and the price of residential land is between the two [35,37]. Land with a lower price will be gradually replaced by land with a higher price. The excessive aspirations of local governments for rapid urban development inevitably led to a lack of vision in urban planning, which intensified the land use conversion in urban built-up areas [35]. Due to the urban land conversion and expansion, the transformation of the urban spatial structure is also happening at the same time. In terms of urban diffusion, Sargolini (2015) pointed out that three different possible scenarios can be profiled [38]. In this work, we consider two scenarios of urban land conversion and expansion. The first scenario is the continuous expansion of urban construction land to replace non-urban construction land. The second scenario is the conversion of one kind of functional urban land to another kind of functional urban land, such as the conversion of industrial land to residential land. This phenomenon is usually caused by the unreasonable arrangement of different kinds of urban construction land in the urban built-up areas due to blind and rapid urban development. In Chinese cities, especially in developing cities, these two scenarios are very common, while the second scenario occurs less frequently in Western cities [35,36].

In China, there is a large gap in the level of development between cities. Cities, such as Beijing and Shanghai, have a high level of development. The intra-urban land use has hardly changed, and the phenomenon of functional urban land replacement is not significant [35]. Land use in developing cities that are undergoing rapid urbanization is changing [10]. The expansion and replacement of urban land coexist. Changchun is a developing city experiencing rapid urbanization and was chosen as the study area here. Therefore, our research methods and conclusions are generally applicable to developing cities, especially in Asia and Africa. Cities in Asia and Africa are still undergoing land use transformation due to rapid urbanization. The rapid urbanization of Asian and African cities will continue, and the urban population will further increase. Therefore, it is necessary to explore the transformation of functional urban land use in the context of rapid urbanization in order to develop a scientific and reasonable urban spatial development strategy.

Based on this, this article will discuss the spatiotemporal evolution of the conversion and expansion of the different types of functional urban land in the central city of Changchun. Functional urban land expansion means transforming non-construction land into urban use at the edge of built-up areas. Functional urban land conversion refers to intra-urban replacement in land use and includes the following two modes: "convert in" and "convert out". The mode of "convert in" refers to the conversion of other kinds of functional urban land into a certain type. The mode of "convert out" refers to the conversion of a certain kind of functional urban land into other types. For example, the "convert in" of residential land means the conversion of other kinds of functional urban land into residential land; the "convert out" of residential land means the conversion of residential land into other kinds of functional urban land. In other words, the conversion of functional urban land is the sum of "convert in" and "convert out" modes. Once we have understood the concept of functional urban land expansion and conversion, then can the analytical method of combining functional urban land expansion and conversion trace the process of urban spatial evolution? Furthermore, is the spatiotemporal process of expansion and conversion consistent across the different types of functional urban land? As we all know, with the expansion of urban space, the importance of the sustainable development of urban space is self-evident [8]. Our research will help to explore the trajectory of urban space evolution, promote the coordinated development of different urban functions, and thus contribute to the sustainable development of urban space.

The paper is organized into the following sections: In Section 1, the research background and the purpose of the research are discussed. In Section 2, we first introduce the study area, then explain the data source, and finally elaborate the research method in detail. In Section 3, we analyze the conversion and expansion of the four types of functional urban land. In Section 4, we discuss the static and dynamic changes of functional urban land conversion and expansion from the perspective of concentric circles and sector modes. The last section is the conclusion of this study.

2. Materials and Methods

2.1. Study Area

Changchun is a developing city, located in northeast China (Figure 1). The functional urban land is undergoing drastic conversion and expansion, which supports this research. Changchun is the capital of Jilin Province. In 2015, the population of Changchun reached 7.54 million, with a total area of 20,594 km^2. The central city, the study area of this article, is the core component of the city and the center of regional economic development, covering an area of 612 km^2. The urban construction land of Changchun is mainly distributed in the central city, with an area of 348.6 km^2 as of 2015.

Roads are the "skeleton" of the urban space, especially the ring road, which helps to analyze the concentric circle pattern of the evolution of functional urban land. The four ring roads, namely the first, second, third, and fourth ring road, divide the central city of Changchun into five zones (Figure 2). The areas of the five zones (Z-1, Z-2, Z-3, Z-4, and Z-5) are 19 km^2, 52 km^2, 99 km^2, 128 km^2, and 314 km^2, respectively. Based on the five sub-zones, we can analyze the concentric features of the conversion and expansion of the functional urban land. In addition to the concentric features, this article also focuses on the sector features of the replacement and expansion of functional urban land, similar to Hoyt's sector mode. With the People's Square as the center, the central city can be divided into eight sectors according to different directions (E, W, S, N, NE, SE, SW, and NW).

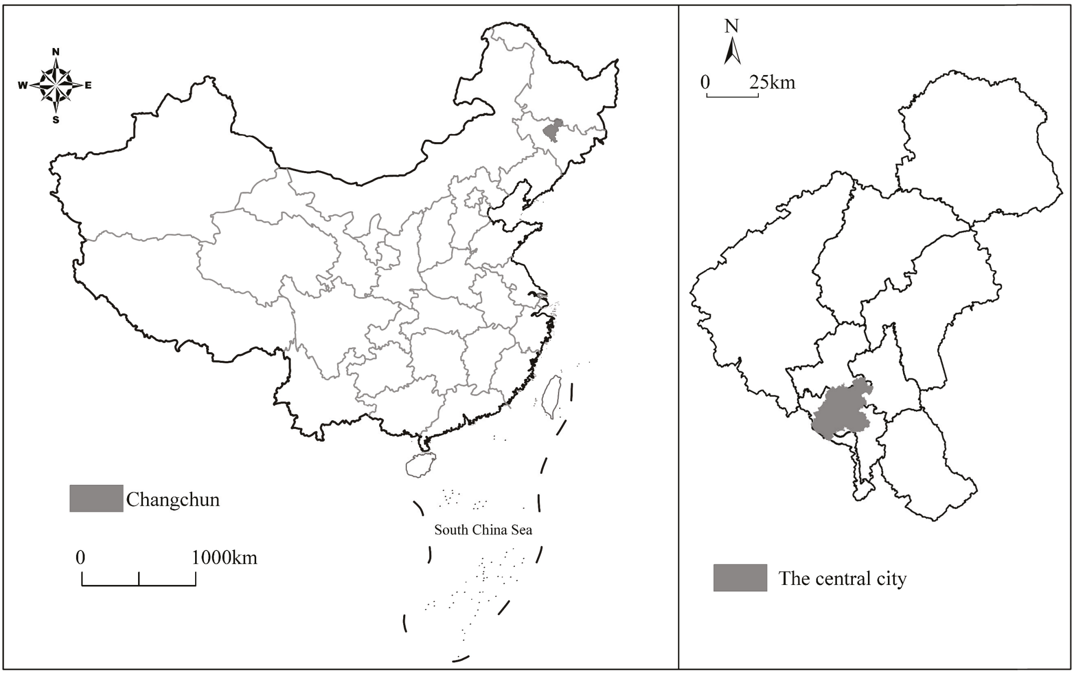

Figure 1. Location of study area.

2.2. Data Sources and Processing

2.2.1. Data Sources

The data used in this article are urban land use maps from 2003, 2007, 2011, and 2015. The source of the urban land use maps is the Changchun city master plan, which can be accessed from the website of Changchun municipal planning and natural resources bureau (http://gzj.changchun.gov.cn, accessed on 25 December 2019). Urban land use maps were the basic data of the Changchun city master plan, and urban planners spent a lot of time creating them based on topographic maps with a scale of 1:100,000 and Google Maps with a spatial resolution of 10 m. Moreover, the urban planners conducted extensive field surveys to identify the dominant uses of parcels that carry multiple functions. Therefore, urban land use maps contain very accurate classification and layout information of functional urban lands. In the maps of urban land use, urban construction land consists of the following eight types of functional urban land: residential land (RL), public service land (PL), commercial land (CL), industrial land (IL), logistic and warehouse land (LWL), road and transport facility land (RTL), green space and square land (GSL), and municipal utility land (MUL). The rest of the Changchun city master plan is also an important support for this paper. In addition, land transaction data obtained from the website of the Changchun planning and natural resources bureau was used to assist in defining the projection of the urban land use maps.

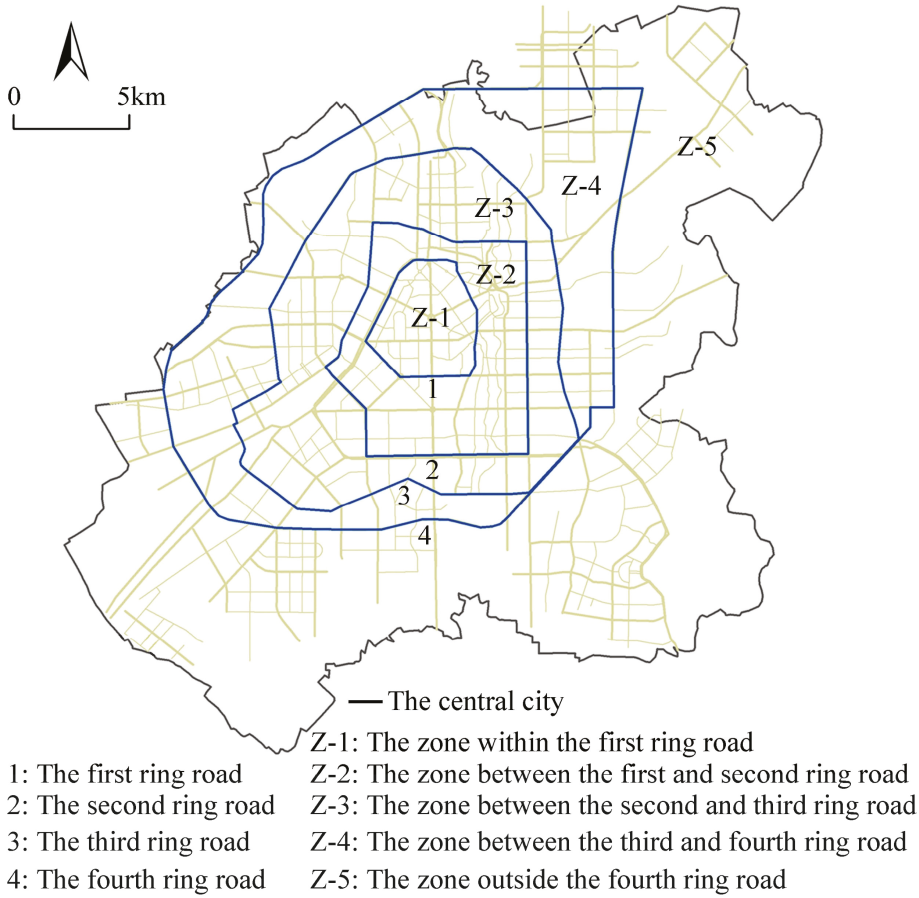

Figure 2. Concentric circle division of the central city.

2.2.2. Data Processing

The file format of the urban land use maps we obtained as JPG. Therefore, we needed to vectorize the urban land use maps. First, the urban land use maps in JPG format were imported into ESRI ArcGIS 9.3 to define the projection (ArcToolbox, data management tools, projections and transformations, define projection). Here, the land transaction data obtained from the website of the Changchun planning and natural resources bureau was used to help georeferenced correction. The land transaction data contains detailed location information and can be easily located in the urban land use maps. Moreover, the land transaction data also contains a coordinate system. Combined with the location and coordinates of the land transaction data, the coordinates of the urban land use maps can be accurately corrected. According to the coordinate system of land transaction data, we used the WGS-84 coordinate system to define the projection. We used the coordinate points of ten transaction plots to conduct spatial corrections of the urban land use maps in JPG format. Then, we vectorized the urban land use maps. In this work, the minimum detected unit is the plot enclosed by the urban road network. After that, we used vectorized urban land use maps and the following methods to analyze the expansion and conversion of functional urban lands. In this paper, the top four types of functional urban land (i.e., RL, CL, PL, and IL) are mainly discussed. The other four types of functional urban land (i.e., LWL, RTL, GSL, and MUL) are collectively referred to as "other land" (OL). The urban land use in the central city for the four years (2003, 2007, 2011, and 2015) is shown in Figure 3.

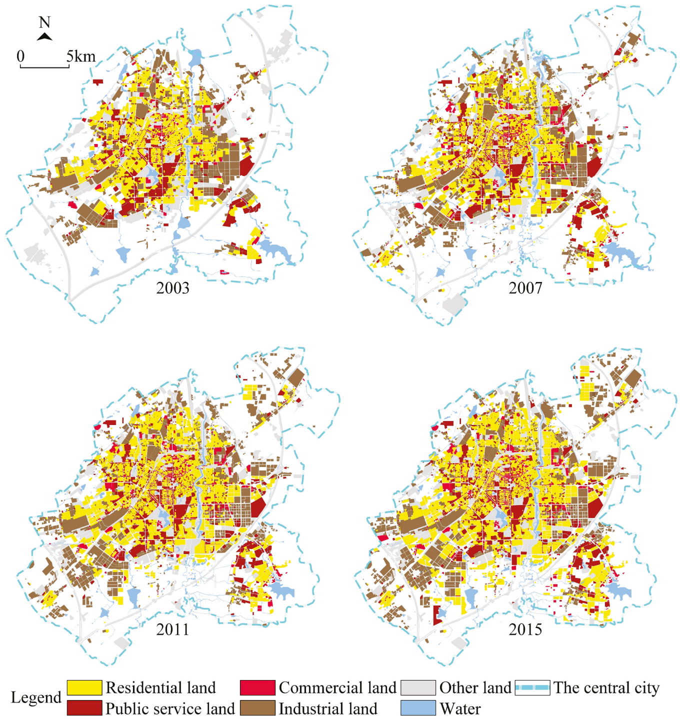

Figure 3. Urban land use maps of the central city (2003, 2007, 2011, and 2015).

2.3. Methods

2.3.1. Overlay Analysis

Overlay analysis was used to study the expansion of functional urban land. Using the ESRI ArcGIS 9.3 software platform, maps of urban land use of the four years (2003, 2007, 2011, and 2015) were overlapped, and expansions of RL, CL, PL, and IL were obtained through overlay analysis. The following equation was used to calculate the spatial distribution of the expansion of the four types of functional urban land and to analyze the spatial features of urban spatial expansion:

$$P_{ij} = \frac{AT_{ij} - At_{ij}}{AT_j - At_j} \tag{1}$$

where P_{ij} represents the proportion of the growth area of j-type urban land in zone i to the total growth area of j-type urban land in the central city; AT_{ij} represents the area of j-type urban land in zone i in the year T; At_{ij} represents the area of j-type urban land in zone i in the year t; AT_j represents the area of j-type urban land in the central city in the year T; At_j represents the area of j-type urban land in the central city in the year t; and t represents the first temporal threshold, while T represents the next temporal threshold.

2.3.2. Transition Matrix

The transition matrix method is an important method for the analysis of functional urban land conversion as it can be used to analyze the number and spatial distribution of conversions between different types of functional urban land [39]. The mathematical expression of the transition matrix is provided in the following equation:

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \quad (2)$$

where S_{ij} represents an area converted from urban land type i to urban land type j; and n represents the number of functional urban land types. ESRI ArcGIS 9.3 and Excel 2016 were used to obtain the transition matrix of functional urban land conversion. First, we used overlay analysis to obtain the intersection layer data (ArcMap, ArcToolbox, analysis tools, overlay, intersect), added a new field to the attribute table of the intersection layer data, calculated the area, and exported the attribute table to a file in DBF format. Then, we used the pivot table in Excel to obtain the transition matrix of urban land use. Thus, we can calculate "convert in" and "convert out" values of the central city and the five zones. The value of functional urban land conversion for the five zones was calculated using the following equation:

$$ULR = C_{in} + C_{out} \quad (3)$$

where ULR is the area of functional urban land replacement; C_{in} represents the conversion of other kinds of functional urban land into this kind of functional urban land; and C_{out} is the opposite of C_{in}.

2.3.3. Kernel Density Estimation

Through the previous overlay analysis and transfer matrix, we have obtained the spatial layout map of functional urban land expansion and conversion. We used the kernel density estimation method for the analysis of the spatial distribution density of functional urban land with the aim of discovering where the land use changes are spatially clustered. The kernel density was calculated as follows:

$$\hat{f}(x) = \frac{1}{nh^d} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \quad (4)$$

where $K(\frac{x-x_i}{h})$ represents the nuclear density equation; h is the threshold; n is the number of points within the threshold; and d is the dimension of the data.

3. Results

3.1. General Characteristics of Functional Urban Land Conversion and Expansion

Judging by the composition of the functional urban land in the central city of Changchun, the sum of the proportions of RL, IL, PL, and CL exceeded almost two-thirds. From 2003 to 2015, the area of urban construction land in the central city increased by 111.24 km^2, of which the four types of functional urban land increased by 81.39 km^2, and their contribution rate reached 73.17%. RL and IL have always been the two largest land types in the central city. The proportion of RL exceeded 30%, while the proportion of IL remained at around 22%.

The area of RL, CL, PL and IL in the three stages increased by 31.13 km^2, 8.66 km^2, 6.88 km^2 and 44.48 km^2, respectively, through functional urban land expansion. The expansion of the functional urban land gradually shifted from the inner ring to the outer ring (Figure 4), and mostly occurred outside of the second ring road from 2003 to 2007, and outside of the third ring road in the latter two stages. From 2003 to 2007, the expansion of the four kinds of functional urban land outside of the second ring road accounted for 98%, including 26% in Z-3, 20% in Z-4, and 52% in Z-5. From 2007 to 2011, the expansion of the four kinds of functional urban land outside of the third ring road accounted for 86%, including 27% in Z-4 and 59% in Z-5. From 2011 to 2015, the expansion of the four kinds of functional urban land outside of the third ring road accounted for 93%, including 25%

in Z-4 and 68% in Z-5. The functional urban land was mainly expanded to the southwest and southeast in the period from 2003 to 2015. Furthermore, from 2003 to 2007, the four kinds of functional urban land also expanded to the northwest and north. In the latter two stages, in addition to the southwest and southeast, the northeast and east were also the main directions for the functional urban land expansion. According to the Changchun city master plan, the government's urban development strategy guided the direction of the urban spatial expansion.

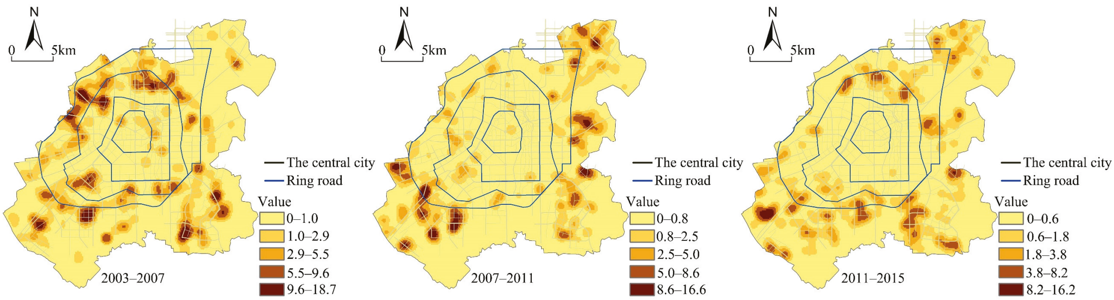

Figure 4. Overall characteristics of the kernel density of the functional urban land expansion. This figure is the kernel density map of the total expanding area of the four types of functional urban land, so the kernel density value is greater than that of a certain type of functional urban land.

Similar to the expansion of functional urban land, the area of functional urban land conversion was also very large. RL, CL, and PL increased by replacing other types of functional urban land, while IL decreased (Table 1). RL increased by 1105.17 ha by "convert in" (2109.73 ha) and "convert out" (1004.56 ha) modes, while CL increased by 100.88 ha and PL increased by 220.08 ha. The "convert in" mode of industrial land was much lower than the "convert out" mode, which resulted in a reduction in IL by 2402.06 ha. The conversion of the functional urban land mainly occurred in Z-1 during the first period, and mainly occurred in Z-3 from 2007 to 2015, which showed a trend of expansion from the inner ring to the outer ring. However, the third ring road was the spatial boundary of the conversion of functional urban land (Figure 5).

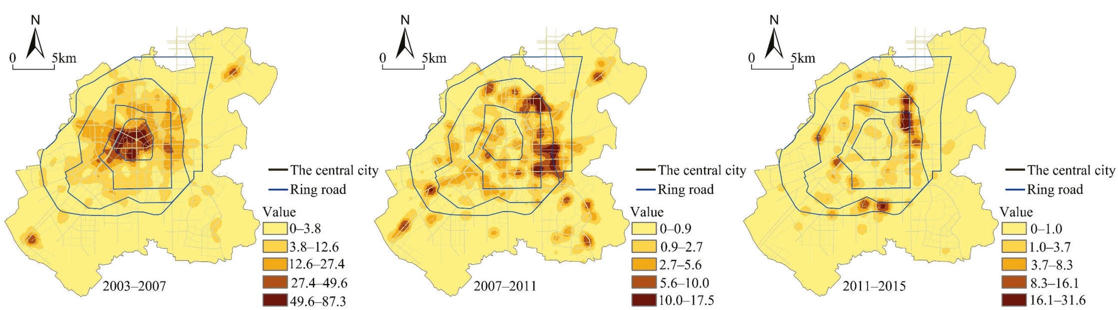

Figure 5. Overall characteristics of the kernel density of functional urban land conversion. This figure is the kernel density map of the total conversion area of the four types of functional urban land, including the area of "convert in" and "convert out", so the kernel density value is greater than that of a certain type of functional urban land.

Table 1. Transition matrix of functional urban land replacement from 2003 to 2015. Unit: ha.

	RL	PL	CL	IL	OL	Reduced Area
RL	-	261.14	328.24	210.54	204.64	1004.56
PL	272.95	-	150.37	95.70	50.92	569.94
CL	176.78	129.40	-	42.71	393.15	742.04
IL	1113.41	187.59	198.08	-	1833.65	3332.73
OL	546.59	211.89	166.23	581.72	-	1506.43
Increased area	2109.73	790.02	842.92	930.67	2482.36	-

3.2. Spatiotemporal Analysis of Conversion and Expansion of Residential Land

With further development, RL increased by 1357.58 ha between 2003 and 2007, 1851.99 ha between 2007 and 2011, and 1478.21 ha between 2011 and 2015. The expansion of RL mainly occurred outside of the second ring road and continued towards the outer ring road. The proportions of RL expansion beyond the second ring road in the three phases were 98.86%, 95.27%, and 99.72%, respectively; the proportions of RL expansion beyond the third ring road were 53.50%, 73.97%, and 91.64%, respectively; the proportions of RL expansion beyond the fourth ring road were 36.50%, 33.36%, and 62.49%, respectively. The residential space was constantly expanding from the inner circle to the outer circle (Figure 6). The directions of residential land expansion were heterogenous, changing from southeast, northwest, and north in 2003–2007 to southeast and east in 2007–2011, and towards the south, north, and northeast in 2011–2015.

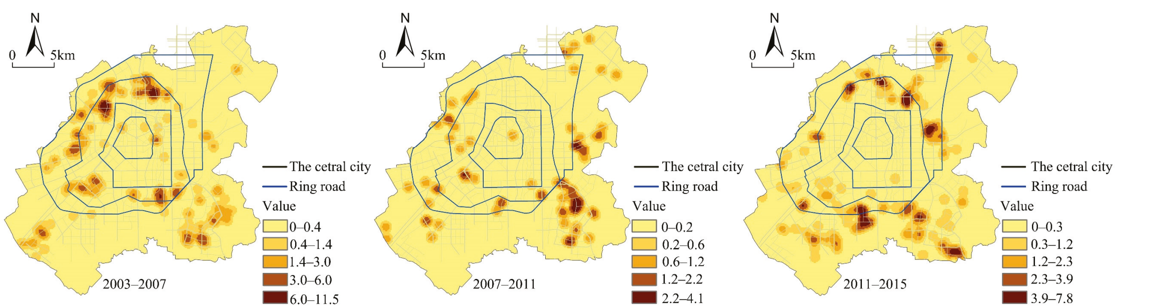

Figure 6. Kernel density map of residential land expansion in different periods.

The conversion of RL was intense from 2003 to 2015, and the "convert in" area of RL was significantly larger than the "convert out" area. Through replacement, residential land increased by 127.16 ha between 2003 and 2007, 569.11 ha between 2007 and 2011, and 408.90 ha between 2011 and 2015. The "convert in" mode of RL during the three periods mainly occurred in Z-1, Z-2, and Z-3. (Figure 7). Due to the suburbanization of industry, IL has mainly been replaced by RL in the inner city. In the east and northeast of the central city, a large area of IL has been converted into RL. The "convert out" of RL mainly occurred in Z-1, Z-2, and Z-3 from 2003 to 2011, and in Z-1, Z-2, Z-3, and Z-4 from 2011 to 2015. Overall, the central city's RL increased continuously from 2003 to 2015.

3.3. Spatiotemporal Analysis of Conversion and Expansion of Commercial Land

Judging by the average area of the expanding CL plots, the increase in commercial space was greatly influenced by the construction of large-scale flagship projects. Often, the development of flagship projects leads to concentric and directional characteristics of commercial land expansion (Figure 8). Combined with the field investigation, we found that the construction of the automobile trade city (on an area of 40 ha) led to the expansion of CL to the west during 2003–2007. The construction of a number of automobile sale and service shops (4S) led to the expansion of CL to the southwest during 2007–2011. The construction of JingYue CBD led the expansion of CL to the southeast. Since these large commercial facilities cover a large area, they were built on the edge of the central city. Therefore, the commercial space of the central city gradually expanded towards the outer circle, and the proportion of CL expansion outside of the fourth ring road was 34.02%, 58.88%, and 92.00% in the three stages, respectively.

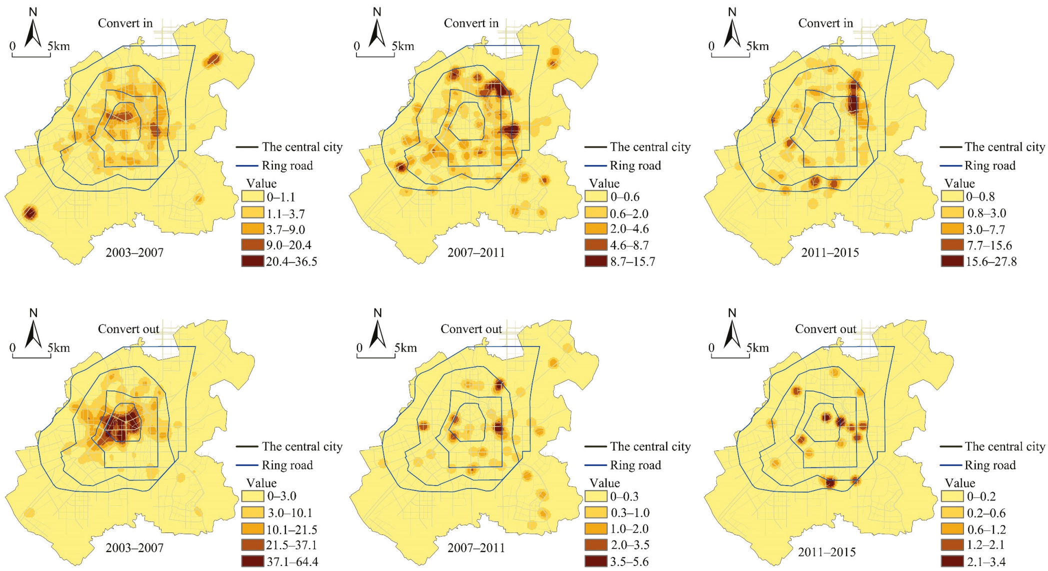

Figure 7. Kernel density map of residential land conversion in different periods.

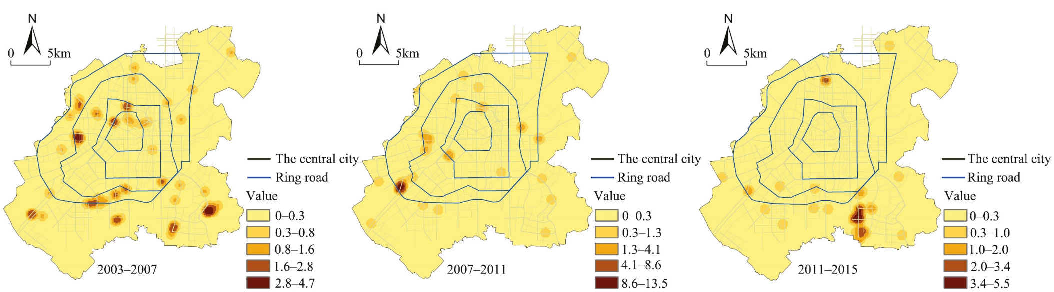

Figure 8. Kernel density map of commercial land expansion in different periods.

In general, with the replacement of functional urban land, the area of CL continued to expand, increasing by 328.07 ha, 85.91 ha, and 38.42 ha in the three stages, respectively. The "convert in" mode of CL mainly occurred within the first ring road during 2003–2007 and was mostly within the third ring road during 2007–2015. Compared to the first period, the "convert in" mode of CL was expanded in the latter two stages. CL has largely replaced IL, indicating that the process of "suppress the second industry and develop the third industry" is continuing. The price of CL is generally higher than that of the other types of functional urban land. Therefore, it is generally rare to replace CL with other kinds of functional urban land. However, in this study, a large area of CL has been replaced by other kinds of functional urban land, especially RL and PL. Field research has shown that CL, replaced by other urban land types, was usually low-grade commercial facilities with chaotic layout and wasted land. The conversion of the functional urban land has thus promoted the integration of this inefficient land into the surrounding built-up environment. The "convert out" mode of CL mainly occurred in Z-1 and Z-2 from 2003 to 2007 and in Z-3 and Z-4 from 2007 to 2011 (Figure 9). In the third stage, the area of the "convert out" of CL decreased sharply and was concentrated only towards the northeast in Z-3.

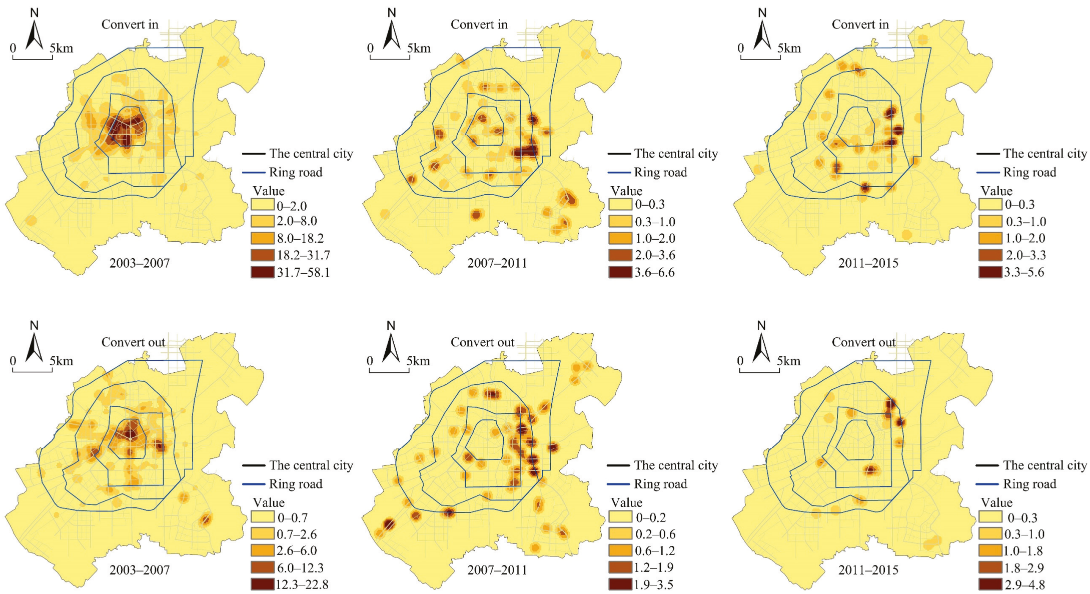

Figure 9. Kernel density map of commercial land conversion in different periods.

3.4. Spatiotemporal Analysis of Conversion and Expansion of Public Service Land

The expansion of PL over the three phases showed that the public service space mainly expanded towards the outside of the southeast in Z-5 (Figure 10). According to the city master plan of Changchun, the ecological environment in the southeast of Changchun is beautiful, and the forest is widespread. The master plan pointed out that the Changchun municipal government has been committed to transforming the area into a "University Town" and a "New Livable Town" since the mid-1990s. Accordingly, universities and exhibition facilities gradually gathered in the area. The relocation of Jilin Jianzhu University and the expansion of Jilin Agricultural University led to this expansion of PL during 2003–2007. In 2007–2011 and 2011–2015, the construction of convention and exhibition facilities, as well as the expansion of universities led to an expansion of PL. The Changchun modern agricultural park, which covers an area of 106 ha, was formally established in 2009. A scientific research institution, the Chinese Academy of Agricultural Sciences, was relocated to the "University Town" in 2011. The educational and exhibition facilities have led to an expansion of PL.

The conversion of PL became less and less frequent from 2003 to 2015. During the period of 2003–2007, an area of 358.97 ha was converted from PL to other urban land types. The area that was converted from the other urban land types to PL was 563.85 ha, resulting in an increase of 204.88 ha in PL. The area of "converted in" was 168.52 ha, and the area of "converted out" was 153.84 ha, indicating an increase of 14.98 ha from 2007 to 2011. From 2011 to 2015, the area of "converted in" was 67.72 ha, and the area of "converted out" was 57.65 ha, indicating an increase of 10.07 ha. The "convert in" and "convert out" modes of PL mainly occurred in Z-1, Z-2, and Z-3 (Figure 11). Similar to the conversion of CL, the replacement of PL has shown that the urban service functions needed to be further improved, especially in Z-1, Z-2, and Z-3. With the continuous improvement of the urban service functions in the inner city, the conversion of PL can be moved from the inner circle to the outer circle. The conversion between residential, commercial and public service lands occurred frequently. From 2003 to 2007, 53.56% of the PL, converted from other urban land types, consisted of RL and CL. However, 75.84% of the PL converted to other urban land types consisted of RL and CL. From 2007 to 2011, 35.25% of the PL, converted from other urban land types, consisted of RL and CL. However, 78.88% of the PL, converted into other urban land types, consisted of RL and CL. From 2011 to 2015, 50.25% of the PL, converted from other urban land types, consisted of RL and CL. However, 99.92% of the PL, converted to other urban land types, consisted of RL and CL.

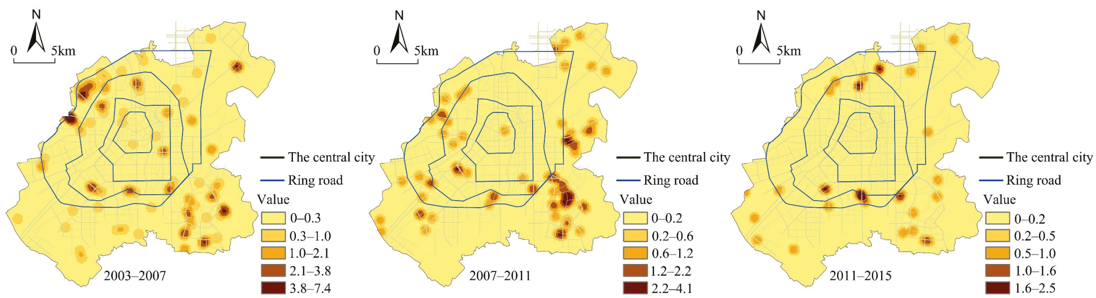

Figure 10. Kernel density map of public service land expansion in different periods.

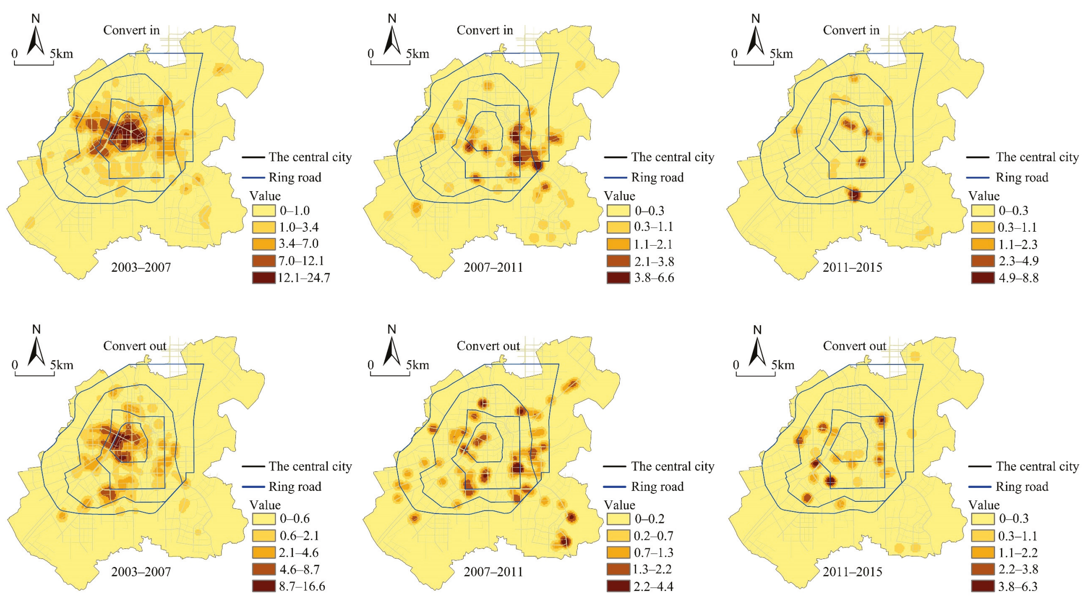

Figure 11. Kernel density map of public service land conversion in different periods.

3.5. Spatiotemporal Analysis of Conversion and Expansion of Industrial Land

The expansion of IL showed predictable spatial characteristics. From 2003 to 2015, there was an expansion of IL mainly towards the southwest in Z-5. The northeast expansion beyond the fourth ring road was added during the latter two stages (Figure 12). It is clear that the southwest and northeast were the main directions of the expansion of IL, while Z-5 was the main circle of IL expansion. Between 2003 and 2007, the proportion of IL expansion in Z-5 accounted for 66.40%. IL expansion in the southwest direction was 44.91%. During the latter two stages, the proportions of IL expansion in Z-5 were 84.19% and 79.95%, respectively. From 2007 to 2011, the proportions of IL expansion in the southwest and northeast were 41.57% and 34.63%, respectively. From 2011 to 2015, the proportions of the expansion of IL in these two directions accounted for 38.68% and 36.80%, respectively. According to the city master plan of Changchun, the automobile industry is the pillar industry of Changchun, and the expansion of the automobile industry in the southwest is the main reason for the observed IL expansion.

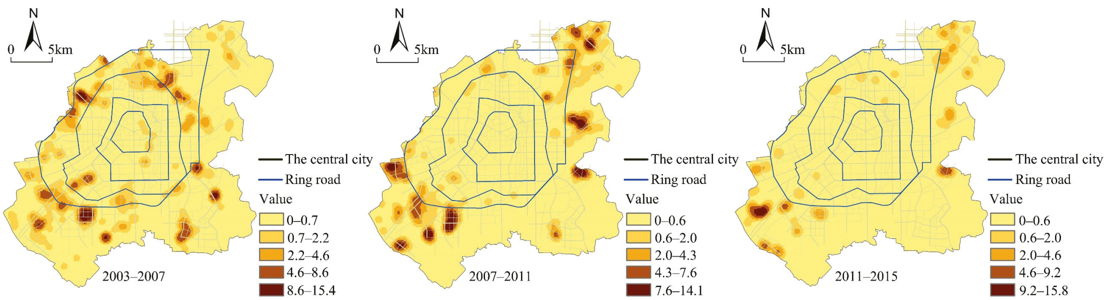

Figure 12. Kernel density map of industrial land expansion in different periods.

From 2003 to 2015, the conversion of IL was very frequent, and IL was continuously replaced by other urban land types (Figure 13). It is clear that IL is constantly being replaced by other urban land types. During all of the three periods, the areas of IL that replaced other urban land types were 834.66 ha, 94.63 ha, and 1.38 ha, respectively; the areas of IL converted into other urban land types were 818.16 ha, 667.46 ha, and 348.03 ha, respectively. The IL "converted out" area exceeded the IL "converted in" area. By replacing IL, it increased by 16.5 ha between 2003 and 2007, decreased by 572.83 ha between 2007 and 2011, and decreased by 346.64 ha between 2011 and 2015. IL was constantly replaced by RL. In all of the three stages, the proportions of the area converted from IL to RL were 38.50%, 75.03%, and 85.52%, respectively. The "convert in" mode of IL mainly occurred in Z-2, Z-3, and Z-4 between 2003 and 2007. In the latter two stages, the "convert in" mode of IL was not obvious. The "convert out" mode of IL in the three periods mainly occurred in Z-1, Z-2, and Z-3. IL in the inner city was gradually moved to the periphery of the city (industrial suburbanization).

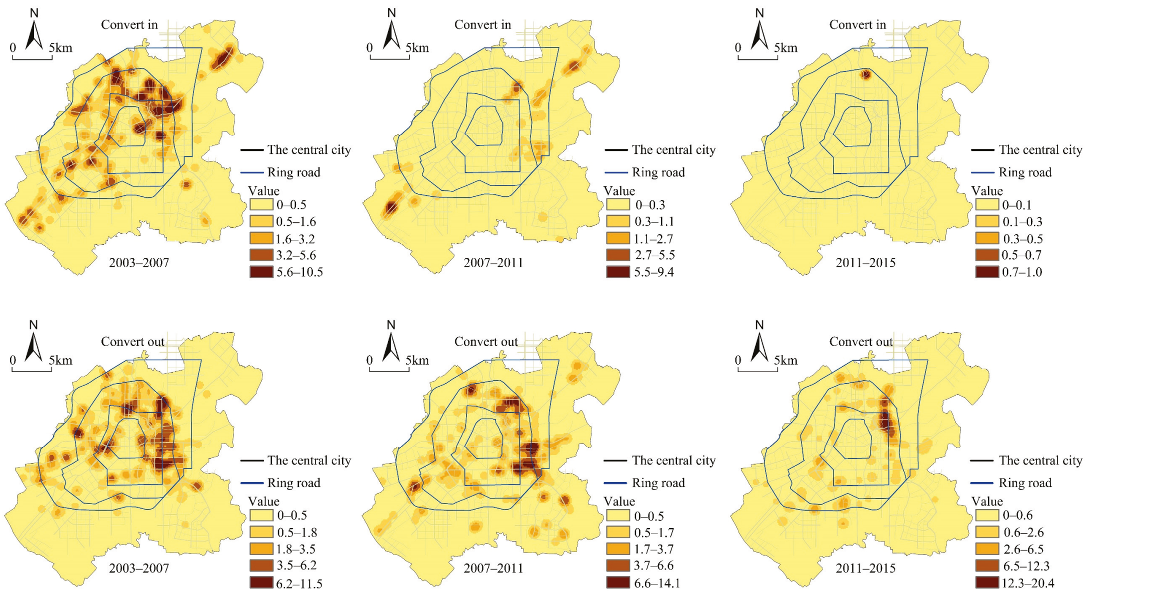

Figure 13. Kernel density map of industrial land conversion in different periods.

4. Discussion

The existing literature on urban space mainly uses urban land expansion data to study urban spatial evolution by comparing the structure of urban space in different years [16–22]. In this study, we explored the dynamic changes of urban space from two perspectives of functional urban land expansion and conversion. Our research demonstrated that functional urban land conversion, similar to functional urban land expansion, is also very common in developing cities. Urban land use maps have facilitated this work. In fact, scholars have been able to identify the different kinds of functional urban spaces or areas through a variety of data [11–13,26]. We suggest that scholars can use the above identified functional urban space or area data to further analyze the replacement between different functional urban land types in order to explore the inherent characteristics of urban spatial evolution. Our work showed that the combination of urban land expansion and conversion can effectively reveal changes in intra-urban space. The structure of urban land use changed slightly from 2003 to 2015. The proportions of RL and CL increased from 27.82% and 3.71% in 2003 to 31.04% and 5.30% in 2015, respectively. The proportions of PL and IL decreased from 11.48% and 23.02% in 2003 to 10.42% and 21.54% in 2015, respectively. The change in urban land use structure is the joint effect of expansion and conversion, but we often ignore the conversion between different types of functional urban land. In addition, using urban land use data at four-year intervals (2003, 2007, 2011, and 2015), our findings prove that functional urban land expansion and conversion in developing cities are very frequent under the process of rapid urbanization. Usually, the topic of urban spatial evolution is studied over a long time period, such as five or ten years [17,18,20,22]. However, our research suggests that for developing cities, the time interval can be shortened, such as the four-year period in this article.

On the basis of the research conducted by Tian et al. (2010) [24], we not only analyzed the concentric characteristics of the functional urban space, but also analyzed the concentration along spatial directions. The concentric characteristics of the expansion of different types of functional urban land are similar, while the directional characteristics are different. RL, CL, PL, and PL have all expanded into the outer circle. RL was mostly expanded into Z-3, Z-4, and Z-5, while CL, PL and IL were mainly expanded into Z-5. RL gradually expanded from the inner circle to the outer circle; the expansion of IL to the periphery was the result of industrial suburbanization, and the construction of large flagship projects has directed the expansion of CL and PL to the periphery. Influenced by urban development strategies and urban planning, the directions of expansion of the four types of functional urban land have shown different characteristics. Southeast, southwest, and south were the main directions for expanding RL; CL expanded in many directions, but there was only one main direction (southeast) for the expansion of PL, and IL has largely expanded to the southwest and northeast.

The conversion of the functional urban land in Z-1, Z-2, and Z-3 showed the characteristics of the transition from the inner circle to the outer circle. The conversion of functional urban land beyond the third ring road was rare. Only the "convert out" mode of RL and CL and the "convert in" mode of IL in a certain period could happen in Z-4. RL, CL, and PL were constantly replacing other types of functional urban land, while IL was constantly being transformed into other types of functional urban land. The conversion area of the four types of functional urban land in Z-1 was large in the first phase and small in the latter two phases. The Z-2 and Z-3 were zones where the area of functional urban land conversion was large in the latter two phases. The "convert in" mode of RL, CL, and PL was mainly located in Z-1, Z-2, and Z-3, which was a process of continuous improvement of the urban functions of the inner city. In the first period, the "convert in" mode of IL was larger than the other three types of functional urban land, and mostly concentrated in Z-2, Z-3, and Z-4. However, in the latter two periods, the "convert in" mode of IL was rare. The "convert out" mode of RL and CL changed from being concentrated in Z-1, Z-2, and Z-3 to being concentrated in Z-1, Z-2, Z-3, and Z-4. The redistribution of public service facilities and the suburbanization of industries have led to the "convert out" mode of PL and IL mainly in Z-1, Z-2, and Z-3.

Our research found that the conversion and expansion of the functional urban land in the central city of Changchun show similar characteristics as the concentric circle and the sector modes. The conversion and expansion of the functional urban land show the obvious characteristics of concentric circles. Influenced by urban planning and urban development policies, the conversion and expansion of functional urban land show predictable fan-shaped (directional) characteristics. The Burgess concentric zone theory and Hoyt's sector theory are static modes of urban spatial structure [24,40,41]. However, the concentric zone mode and the sector mode are not static for a developing city but are dynamic. In other words, the static layout of urban space exhibits concentric circles and fan-shaped characteristics, and the evolutionary process of urban space also exhibits concentric circles and fan-shaped characteristics for developing cities. The conversion and expansion of the different functional urban lands show different concentric circles and fan-shaped characteristics at different periods. The expansion of RL, CL, PL, and IL shifts from the second ring road to the third ring road. The direction of expansion of RL, CL, PL, and IL in the three stages is different. The conversion of RL, CL, PL, and IL also show dynamic changes in the concentric circles and in the fan-shaped characteristics.

Our research will provide theoretical support for the coordinated development of different types of functional urban space in different areas of a city. The coordinated development of urban space will further contribute to the optimization of urban spatial structure and will promote the sustainable development of urban space. However, this study has one main shortcoming. We only studied urban space from the perspective of functional urban land. Urban space is complex, and apart from land, it also covers other elements such as population, architecture, transportation, society, and culture. In general, it is biased to explore the evolution of urban space using a single criterion rather than multiple criteria. We therefore should consider additional development elements to overcome this shortcoming in future research, rather than only using a single criterion. Moreover, it should also be noted that urban land use is one of the most important indicators of urban space and can effectively decode the geospatial pattern of cities. Our study proves that the phenomenon of intra-urban land transformation brought by rapid urbanization is common and needs to draw the attention of urban policy makers and decision makers to scientifically adjust the strategy of urban spatial development. We hope that this research will be open to other researchers who study urban space from different perspectives in order to obtain inspiration for urban research. In addition, the quantitative methods we used are retrospective tools. We will introduce predictive tools to study the temporal and spatial changes in the replacement and expansion of functional urban spaces in the future in order to better optimize the urban spatial structure.

5. Conclusions

With the help of urban land use maps and other auxiliary data, we analyzed the temporal and spatial characteristics of the replacement and expansion of different types of functional urban land using overlay analysis, transition matrix, and kernel density estimation methods. The results prove that the analysis of the replacement and expansion of functional urban land can reflect the dynamic evolution of urban space in the context of rapid urbanization. This research showed that changing the structure of land use in cities and expanding and replacing the functional urban land can be used to analyze whether the urban spatial structure has stabilized. The conversion and expansion of functional urban land in the central city of Changchun is still very active, which indicates that urban spaces have not yet stabilized and that they still require continuous improvement. When one kind of functional urban land replaces other kinds of functional urban land, there is further replacement by other kinds of functional urban land. This study demonstrated changes between RL, CL, PL, and IL. Combined with changes in the structure of the land use in cities, suggestions can be made for the future layout of urban land, and the urban spatial structure can be adjusted in order to promote sustainable urban spatial development.

The temporal and spatial characteristics of urban spatial evolution are a classic research theme involving multiple disciplines of urban planning, geography, and economics. The spatiotemporal changes in the functional urban land evolution and the path of optimization of urban spatial structure were explored in order to support the reasonable development of urban space. As we mentioned in the Introduction section, our research methods and conclusions are generally applicable to developing cities around the world in order to help urban policy makers propose sound strategies for the scientific development of urban spaces.

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Article

Spatiotemporal Dynamics of Soil Impermeability and Its Impact on the Hydrology of An Urban Basin

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Abstract: The presence of impervious surfaces in catchments interferes with the natural process of infiltration, which has a marked influence on the hydrological cycle, affecting the base flow in rivers and increasing the surface runoff and the magnitude of flood flows. Like many Latin American cities, Loja (located in southern Ecuador) has experienced significant rates of urban growth in recent years, increasing the impervious surfaces in the catchment where it belongs. The aim of this study is to analyze the spatiotemporal dynamics of imperviousness in the study area for the period 1989–2020, using the Normalized Difference Impervious Surface Index (NDISI) and the supervised classification of Landsat images. The effect on flood flows was studied for each timestep using HEC-HMS hydrological model. Additionally, a future scenario of impervious surfaces was generated considering the observed spatiotemporal variability, possible explanatory variables, and logistic regression models. Between 1989 and 2020, there was an increase of 144.12% in impervious surfaces, which corresponds to the population growth of 282.56% that occurred in the same period. The period between 2001 and 2013 was the one that presented the most significant increase (1.06 km^2/year). A direct relationship between the increase in impervious surfaces and the increase in flood flows was observed, reaching a significant variation towards the horizon year that could affect the population, for which measures to manage the surface runoff is necessary.

Keywords: urban hydrology; impervious surfaces; land use scenarios; urban surface growth; hydrological model; flood flows

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1. Introduction

Features such as climate, topography, vegetation, and coverage of a natural watershed produce a natural water cycle and a given hydrological response. Different factors such as the impervious surfaces can affect this unique natural hydrological process and cause adverse effects to the catchment [1].

The impervious surface is usually defined as the collection of anthropogenic landforms that water cannot directly infiltrate into, including rooftops, roads, and parking lots [2,3]. The urbanization process has significant impacts on the hydrology of a basin; as urban areas expand, permeable and moisture-holding lands transform into impervious surfaces such as concrete and asphalt, causing a decrease in infiltration and base flow, as well as an increase in flood flows and runoff volumes. The storm drainage systems simplify the natural drainage systems, altering the response of the basin to precipitation events since shorter concentration and recession times occur [1,4,5]. On the other hand, the dynamics of impervious surfaces impact urban regional climate by altering the thermal environment and water quality [3,6].

Several studies have analyzed the effect of urbanization [7–9], land-use changes [10–14], or impervious cover change [15,16] on Hydrology.

Remote sensing has been extensively utilized for the detection of impervious surfaces [17,18]. The approaches have been diverse: index-based methods, classification-based methods, and mixture analysis. The index-based methods include indices such as normalized difference buildup index (NDBI) [19], normalized difference impervious surface index (NDISI) [20], modified NDISI (MNDISI) [21], biophysical composition index (BCI) [22], and perpendicular impervious surface index (PISI) [23]. The classification and regression approaches include maximum likelihood classifier [24], support vector machine [25], artificial neural networks [26], random forest [27], and object-oriented methods [28]. For the mixture analysis, spectral mixture analysis (SMA) [29] and temporal mixture analysis (TMA) [30] are applied.

Urbanization is a worldwide trend. Currently, more than 50% of the world's population lives in urban centers, and more than 500 cities in the world have a population above 1 million inhabitants [5]. The reasons for urban growth are diverse; in Latin American cities, we could highlight the natural demographic growth, migration from the countryside to the city in search of better living conditions, changes in the location patterns of economic activities, and housing, among others.

Several cities in Ecuador have experienced rapid growth, which is evidenced in a notable increase in the urbanized area in recent years. One of those cities is Loja, capital of the province of the same name, located south of Ecuador and bordering Peru. This study analyzes the influence of urban growth on the hydrology of the basin where the city is located and on the extreme flow events that occur in it. For this, using aerial photographs and satellite images, a Normalized Difference Impervious Surface Index (NDISI) was calculated, and a multitemporal analysis of the urban surface variation was carried out. Then, flood flows for various coverage scenarios were generated using precipitation data and applying a hydrological model to finally evaluate the effect of these flows over the areas surrounding the riverbanks in various points of interest. The study of the spatiotemporal variation of the impervious surfaces using a spectral index and supervised classification of images, combined with statistical techniques and artificial intelligence to define future scenarios of impervious surfaces, and the evaluation of their possible impacts through hydrological modeling, are the newest aspects of the present work.

2. Materials and Methods

2.1. Study Area

The Zamora River (A = 227 km^2) is a tributary of the Santiago River and part of the hydrological system of the Amazon River. The Zamora River basin is located in the southern Andes of Ecuador, has an average height of 2400 m above sea level, an average slope of 30%, and an average slope of the main channel of 8.3% [31]. The basin is covered by vegetation in good condition, mainly composed of grasslands, scrublands, and forests [32]. Its climate is subhumid equatorial temperate, with a mean annual precipitation depth of 909.1 mm. The Zamora River presents dry periods between May and November and can present important flows during the rainy season (from December to April) [33]. The Zamora River, up to its pour point (79°13′28″ W, 3°55′17″ S) has six main tributaries that make up a network of 102.70 km in length, with the main channel of 22.89 km, which has stream order three, according to the Horton—Strahler Laws. The city of Loja occupies the middle and lower portion of the basin. The city has about 200,000 inhabitants and an area of 43 km^2, being the only existing urban area in the Zamora River basin. The growth of the city in the last 30 years, as well as the construction and improvement of the road network, has created impervious zones.

The location of the study area is presented in Figure 1.

2.2. Data Collection

Three image sets, acquired from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI)-Thermal Infrared Sensor (TIRS) were collected in the study area [34]. Their acquisition dates, spectral bands, and spatial resolutions are listed in Table 1. Atmospheric correction was performed to each image using the Atmospheric/Topographic Correction for Mountainous Terrain (ATCOR) software developed by the German Aerospace Center, Wessling, Germany [35]. The Landsat images archived in the U.S. Geological Survey (USGS) data clearinghouse have been georectified [36]. All images in Table 1 are geometrically matched to each other.

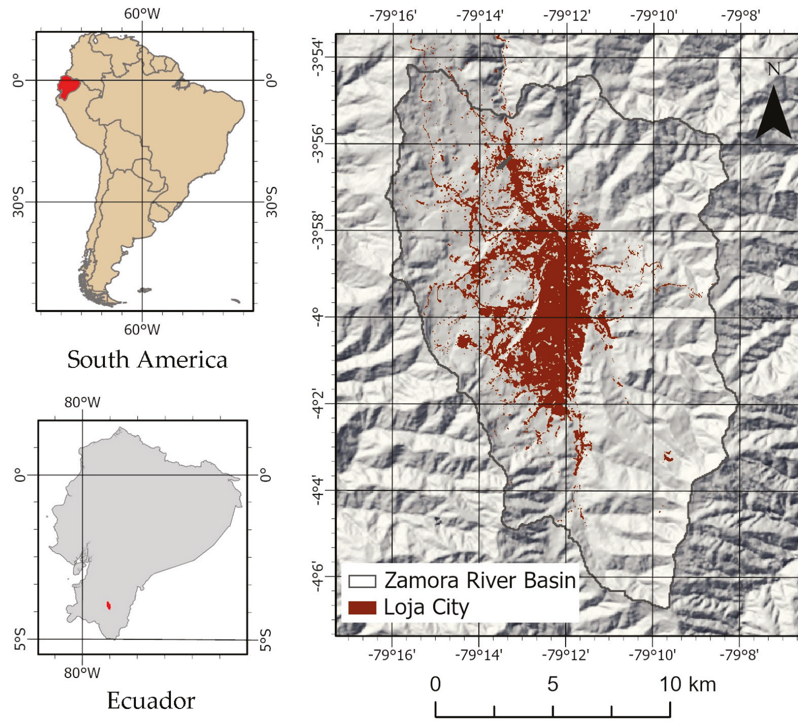

Figure 1. Location of the study zone.

Further, historical information on the type and land use of the study area was collected [37], which was used in the hydrological modeling component of this study.

2.3. Analysis of Impervious Surfaces

The Normalized Difference Impervious Surface Index (*NDISI*) [20,38] is used to enhance impervious surfaces and suppress land covers such as soil, sand, and water bodies.

$$NDISI = \frac{T_b - (MNDWI + NIR + SWIR1)/3}{T_b + (MNDWI + NIR + SWIR1)/3} \quad (1)$$

T_b refers to the brightness temperature of the TIRS1 thermal band. *MNDWI* represents the Modified Normalized Difference Water Index (Equation (2)), *NIR* refers to the pixel values extracted from the near-infrared band. *SWIR1* refers to the pixel values extracted from the first shortwave infrared band.

$$MNDWI = \frac{G - SWIR1}{G + SWIR1} \quad (2)$$

G represents the pixel values extracted from the green band.

Table 1. Satellite images from the three Landsat sensors (TM, ETM+, OLI-TIRS) used in this study.

Satellite	Sensor	Acquisition Date	Resolution (m)	Wavelength (μm)
Landsat-5	TM	10 November 1989	30	Band1 (Blue): 0.441–0.514 Band2 (Green): 0.519–0.601 Band3 (Red): 0.631–0.692 Band4 (NIR): 0.772–0.898 Band5 (SWIR-1): 1.547–1.749
			120	Band6 (TIR): 10.31–12.36
			30	Band7 (SWIR-2): 2.064–2.345
Landsat-7	ETM+	3 November 2001	30	Band1 (Blue): 0.441–0.514 Band2 (Green): 0.519–0.601 Band3 (Red): 0.631–0.692 Band4 (NIR): 0.772–0.898 Band5 (SWIR-1): 1.547–1.749
			60	Band6 (TIR): 10.31–12.36
			30	Band7 (SWIR-2): 2.064–2.345
			15	Band8 (Pan): 0.515–0.896
Landsat-8	OLI-TIRS	28 November 2013 11 August 2020	30	Band1 (Coastal/Aerosol): 0.435–0.451 Band2 (Blue): 0.452–0.512 Band3 (Green): 0.533–0.590 Band4 (Red): 0.636–0.673 Band5 (NIR): 0.851–0.879 Band6 (SWIR-1): 1.566–1.651 Band7 (SWIR-2): 2.107–2.294
			15	Band8 (Pan): 0.503–0.676
			30	Band9 (Cirrus): 1.363–1.384
			100	Band10 (TIR-1): 10.60–11.19 Band11 (TIR-2): 11.50–12.51

Applying Equation (1), NDISI images were generated for each of the collected images (Table 1). A manually adjusted threshold was used to extract impervious surface features from the NDISI images generated. The pixels with values greater than the threshold are impervious surfaces and were assigned a value of 1, while the pixels with values equal to or less than the threshold are nonimpervious surfaces and were assigned a value of 0. Thus, the resultant image is a binary image, only showing the extracted impervious surfaces.

Additionally, the supervised classification of the collected images was carried out using the maximum likelihood method [39] in order to obtain the urban area (impervious surface) and its temporal variation and maps of the impervious and nonimpervious surface for the study area.

The performance of the NDISI and the supervised classification for the detection of impervious surfaces was evaluated by visual comparison with the images included in Table 1. Using the results of the technique that offered the most reliable results, the spatiotemporal analysis was performed, as well as the generation of scenarios towards the year 2030 and hydrological modeling in order to study the impact of the variation of impervious surfaces on the hydrology of the basin under study.

2.4. Spatiotemporal Analysis of Impervious Surfaces and Scenario Generation

Once the maps of the impervious and nonimpervious surface were obtained, the changes that occurred between 1989 and 2001 were analyzed, relating them to the possible explanatory variables to obtain a predictive model that could be validated by comparison with the coverage obtained for 2013.

The changes that occurred were studied by applying the methodology proposed by [40], which allows determining the persistence, gain, loss, and exchanges between the thematic categories considered in each land occupation map through the analysis of a cross-tabulation, identifying the transitions that occurred between 1989 and 2001. The relationships between the observed transitions and their possible explanatory variables are called transition submodels. The number of transition submodels will be equal to the number of transitions that occur in the study area; it is possible to group several transitions into a single model when it is considered that these are the product of the same causes. Each transition model includes a certain number of explanatory variables, which can be selected based on their explanatory potential, calculated by Cramer's V coefficient, or by testing various combinations of explanatory variables until the optimal fit between transitions and explanatory variables is obtained. Cramer's V values greater than 0.4 are acceptable [41]. Three explanatory variables were considered: Elevation (using a digital elevation model—DEM), which influences the presence of different types of vegetation; the slope, which limits urban growth; and the distance to streets and roads, which motivates and facilitates urban growth.

The transition submodels were calculated by logistic regression and by means of a multilayer perceptron neural network (MLP), obtaining the probability of occurrence of each transition according to the selected explanatory variables. Logistic regression [42] allows establishing a relationship between a binary dependent variable (transitions) and the explanatory variables considered, modeling their probability of occurrence according to the latter.

Neural networks of multilayer perceptrons are formed by a set of simple elements (neurons or perceptrons) distributed in layers and are connected to the intermediate layer or layers by means of activation functions. These functions are defined from a series of weights or weighting factors that are calculated interactively in the learning process of the network. The objective of this learning is to estimate known results (observed transitions) from some input data (explanatory variables); to later calculate unknown results from the rest of the input data. Learning is carried out from all the units that make up the network, varying the set of weights in successive interactions [39].

The land cover change modeling towards the horizon year (2013) was carried out applying Markov chains; using the land cover map of the end date (2001) along with the transition probability matrix previously calculated, to determine the zones are that will undergo a transition from the end date to the prediction date (2013).

The future land cover map was modeled using a multiobjective land-use allocation procedure (MOLA) [41,43]. Considering all transitions and using the selected explanatory variables, a list of host classes (which would lose some area) and a list of demanding classes (which would gain some area) are created. Loss or gain areas are determined by Markov chains and through the multiobjective allocation procedure, in which the explanatory variables determine the most suitable places for each change in occupation. Land from all host classes is allocated to all demanding classes. The results of each land occupation reallocation are overlaid to produce the final result [41]

Two maps were generated to predict land cover for the year 2013 based on the modeling of the relationships between the observed changes and the explanatory variables. These relationships were modeled with logistic regression and neural networks. For the validation, the map extracted from the 2013 image was considered as a reference, and, through confusion matrices, the correspondence between the reference map and those obtained through neural networks and logistic regression was studied. Forecast errors of land cover were determined for each model proposed, as well as omission and commission errors that may have occurred.

From the confusion matrix, the global reliability of the classification was calculated as the relationship between the number of pixels correctly assigned and the total number of pixels in the image [39]. Complementarily, the fit between the reference map and the maps generated was calculated using the Kappa index [40]. After analyzing the adjustment, we proceeded to generate a land cover map towards the year 2030, considering the land cover maps of 2013 and 2020, the explanatory variables selected for each transition, and applying the model that presents the best capacities.

The spatiotemporal analysis of impervious surfaces and scenario generation described was carried out by applying the land change modeler module of TerrSet 2020 [41].

2.5. Hydrological Modeling

The HEC-HMS model was developed to study the response of the Zamora River basin to extreme precipitation events, considering the different stages of urban growth in the city of Loja. The basin topology was developed based on a digital elevation model generated using a contour map at 1:50,000 scale [44]. This topological model included contributing sub-basins, junction points in which the contributions of the sub-basins are added, sections of the river network in which the hydrologic routing of the hydrographs is carried out, and the outlet point of the basin in which the flow resulting from the rain-runoff simulation is obtained. The topological model is presented in Figure 2.

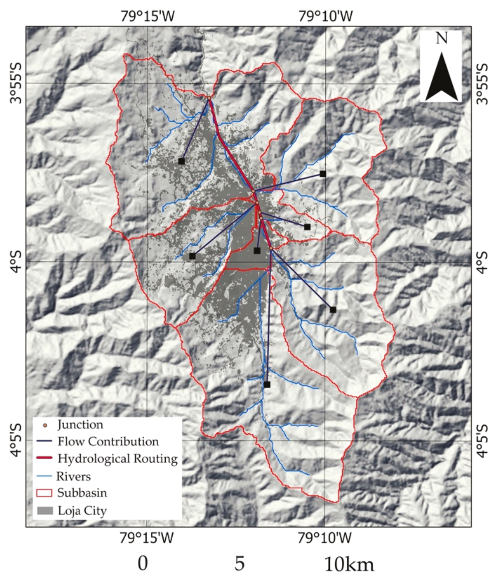

Figure 2. Topological model of the Zamora River basin.

Synthetic storms were generated for return periods of 10, 25, 50, and 100 years, using intensity equations determined for the city of Loja [45].

$$I_{TR} = 92.854 Id_{TR} t^{-0.4083} \tag{3}$$

$$I_{TR} = 480.74 Id_{TR} t^{-0.8489} \tag{4}$$

where Id_{TR} is the maximum intensity for a given return period, t is the duration of the storm in minutes, I_{TR} is the intensity in mmh^{-1}. Equation (1) is valid for durations between 5 and 43 min, Equation (2) is valid for durations between 43 min and 1440 min.

Abstractions were quantified using the curve number (*CN*) methodology of the U.S. Soil Conservation Service (USSCS) [4,46] for normal conditions, calculating the *CN* for each hydrological response unit obtained according to the intersection of type and land use for each date considered. The transformation of surface runoff into flow was carried out by applying the USSCS Unit Hydrograph. For the hydrologic flow routing, the Muskingum-Cunge method was applied. The concentration and delay times of each sub-basins were determined using the Kirpich formula [4,46].

3. Results and Analysis

3.1. Analysis of Impervious Surfaces Using NDISI

Figure 3 shows the temporal variation of the NDISI index. A visual comparison with the collected images allowed us to determine that the consolidated areas of the city center are identified in an acceptable way through the NDISI index. The areas surrounding the city center were consolidated as urban areas over time, and in the process, a transition is observed from the heterogeneous mixture of impervious and green areas to consolidated urban areas. The impervious surfaces of the southwestern portion of the city were underestimated in all analyzed images. Land surface emissivity (ε) varies with land cover on the ground surface. In urban environments, surfaces with vegetation have a higher thermal retention capacity and, therefore, have greater cooling effects than areas without vegetation [47], which is reflected in the temporal variation of the NDISI.

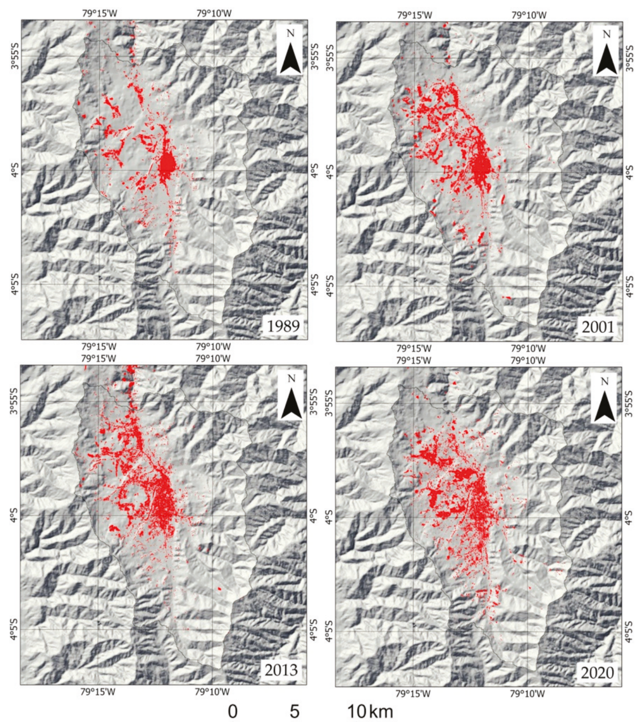

Figure 3. Spatiotemporal dynamics of impervious surfaces using NDISI: Period 1989–2020.

In suburban–rural areas, impervious areas have been identified to the west of the city. These areas do not correspond to urban areas but to surfaces with bare soil due to fallow agricultural areas or small areas under construction that have just been cleared. On the other hand, the selected images were taken between August and November (which are part of the dry season) to ensure less cloud cover. Therefore, during that period, the vegetation cover is less vigorous and frequently leaves the soil exposed. In Landsat images, bare soil is often mistaken for impervious surfaces due to their similar spectral characteristics, resulting in noisy salt and pepper appearances in supervised image classification [47]. Furthermore, the thermal response of the soil is quite similar to that of the impermeable surface, which causes spectral confusion between impermeable areas and bare soil when classifying it [20,48].

Despite its acceptable performance, it was considered that the NDISI and its temporal analysis were not completely adequate to study the evolution of the impervious surfaces in the study area.

3.2. Analysis of Impervious Surfaces by Supervised Classification

Figure 4 shows the impervious surfaces in the study area determined by supervised classification applying the maximum likelihood criterion. A visual comparison with the collected images shows an adequate representation of the impervious surfaces and their spatiotemporal variation, which is why they are selected for the following phases of the study.

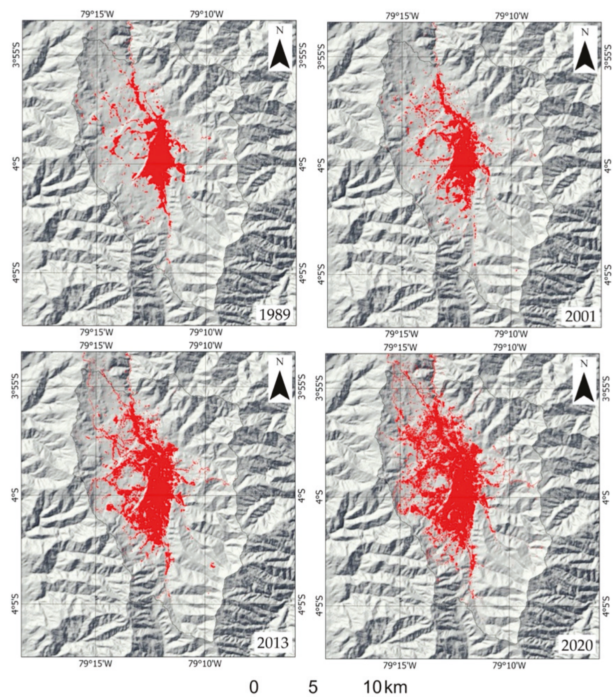

Figure 4. Spatiotemporal dynamics of impervious surfaces using supervised classification for 1989–2020.

A summary of the area occupied by the city (impervious surfaces) and its respective population at each year considered is included in Table 2.

Table 2. Variation of urban area and population in the city of Loja. Period 1989–2020.

Year	Impervious Surface			Population		
	Area (km^2)	Increase (%) *	Annual (km^2/year)	Total (PPL)	Increase (%) *	Density (PPL/km^2)
1989	17.68	0	0	71,652	0	4052.71
2001	20.18	14.17	0.21	118,532	65.43	5873.74
2013	32.87	85.97	1.06	185,321	158.64	5638.00
2020	43.15	144.12	1.47	274,112	282.56	6352.54

* Reference year: 1989.

Table 2 includes a summary of the area occupied by the city (impervious surface), which was determined through the supervised classification, as well as its respective population at each year considered. For the period between 1989 and 2020, there is an increase of 144.12% in impervious surfaces, which corresponds to the population growth of 282.56% that occurred in the same period. Furthermore, there is a very significant increase in the annual variation of the impervious surfaces in the period between 2001 and 2013 (1.06 km^2/year), which is linked to the receipt of money remittances sent by a large number of Ecuadorian citizens who emigrated overseas as of 1999. The population density shows a significant growth between 1989 and 2001, but in 2013 it reduced probably due to the mentioned migratory process that Ecuador experienced during the first decade of this century. By 2020, the population density recovers an increasing trend.

Figure 5 presents the variability of the impervious surfaces in the periods 1989–2001, 2001–2013, and 2013–2020. In the period 1989–2001, growth was observed based on the consolidation of the areas adjacent to the downtown, with the areas located to the southeast and north of the city achieving further development. The greatest increase in impervious surfaces occurred between 2001 and 2013, with the highest incidence in the southwest of the city, which, at that time, already had basic infrastructure which facilitated urban development. Something similar was observed in the east of the city, although on a smaller scale. For its part, in the 2013–2020 period, urban development was directed towards the west of the city, which, due to its better topographic conditions, has become the ideal place for the growth of the city.

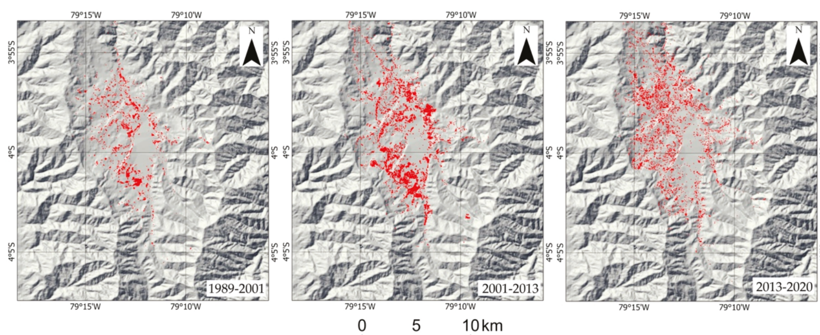

Figure 5. Variability of impervious surfaces by period analyzed.

3.3. Change Detection

Table 3 presents a summary of the cross-tabulation of data for the period between 1989 and 2001. As shown in the table, there is a predominance of persistence in all covers. There are 224.97 km^2 of stable areas, equivalent to 98.90% of the total study area, and 2.51 km^2 of zones that have undergone changes, corresponding to 1.10% of the total area. There is an increase in urban areas and a consequent decrease in rural areas that were occupied before the urban expansion occurred.

Table 3. Cross-tabulation of land cover between 1989 (columns) and 2001 (rows).

	Nonimpervious	Impervious	Total
Nonimpervious	207.30	0	207.30
Impervious	2.51	17.68	20.18
Total	209.80	17.68	227.48

3.4. Explanatory Variables

Table 4 shows the measure of association between the explanatory variables and the land covers present in the study area. Cramer's V value fluctuates between 0.1 and 0.3. The slope is the variable that has the greatest association with the existing land cover categories (Table 4); this is because the slope affects urban expansion, as well as land use in rural areas, such as crops or the presence of natural forests. Another important explanatory variable is the elevation (DEM), which conditions urban expansion.

Table 4. Creamer's V values: measure of association between quantitative explanatory variables and land covers studied.

	Nonimpervious	Impervious
DEM	0.3832	0.4970
Slope	0.4387	0.6591
Distance to roads	0.3184	0.4344
Distance to rivers	0.0367	0.0236

The distance to roads has an acceptable Cramer's V, corroborating the initial assumption that the presence of roads encourages urban expansion. The values of Cramer's V for distances to rivers are <0.1, probably because there is no strict regulation of urban expansion in areas near rivers.

3.5. Transitional Submodels

Table 5 shows the transition submodels, their respective variables, and the results of the calculated logistic regression. The coefficients that affect each explanatory variable are included in the logistic regression equation and the correlation between variables and transitions (ROC).

Table 5. Logistic regression results: Modeled transition (transition submodel), correlation (ROC), explanatory variables, and coefficients of each explanatory variable in the regression equation.

Transition	ROC	Variables	Coefficient
From Nonimpervious to impervious	0.9508	Intercept	7.8911
		DEM	−0.0032
		Slope	−0.1251
		Distance to roads	−0.5805

Table 6 shows the inverse relationship between the transition from nonimpervious to impervious surfaces and all the variables considered in the transition model. Chances of urban expansion are reduced when there is higher elevation, steeper terrain, and longer distances to roads. The degree of correlation between the transition studied and the explanatory variables is high, around 95%. Table 6 shows the results of the neural network application. The learning rate is low, about 1/1000, with a training and validation error of about 2/10, which is well above the acceptable error (RMS). This demonstrates the limited performance of neural networks in the present case, even though the accuracy rate is greater than 90%.

The transition probabilities for the land cover considered are included in Table 7. It can be seen that the probability of maintaining the same land use predominate, reaching almost the value of 1 in the case of nonimpervious surface and with values >1 in the case of impervious surface. As expected, the impervious surface is not likely to change to a nonimpervious surface, whereas the impervious surface is always the same.

Table 6. Results of the application of neural networks.

Parameter	Value
Neurons input layer	3
Neurons hidden layer	2
Output layer neurons	2
Samples requested by class	3112
Final learning rate	0.0003
Boost factor	0.5
Sigmoid constant	1
Acceptable RMS	0.01
Iterations	10,000
RMS training	0.2595
RMS test	0.2651
Accuracy rate	91.23%
Skill measure	0.8245

Table 7. Probability of transition between land uses.

	Nonimpervious	Impervious
Nonimpervious	0.9937	0.0063
Impervious	0	1

Table 8 shows the confusion matrix between the map extracted from the 2013 image and the map generated by neural networks (MLP). Table 9 shows the confusion matrix between the map extracted from the 2013 image and the map generated by logistic regression (LogReg). In both tables, the comparison of the maps shows a predominance in the number of pixels that have the same thematic class. The largest errors occur when the nonimpervious surface has been modeled as an impervious surface (1497 and 1493 pixels). The errors in which the impervious surface was modeled as a nonimpervious surface are lower (289 and 285 pixels). Similarly, commission errors vary between 0.61% and 3.68%, and the maximum value corresponds to the impervious surface in both tables. The errors of omission vary between 0.12% and 16.51%, having the highest error by the commission in the transition to impervious surface

Table 8. Confusion matrix between the map extracted from the 2013 image and the map created through neural networks (MLP).

	2013 Map (Reference)			
	Nonimpervious	Impervious	Total	Commission Error (%)
Map 2013 (MLP)				
Nonimpervious	243,834	1497	245,331	0.61
Impervious	289	7568	7857	3.68
Total	244,123	9065	253,188	
Omission error (%)	0.12	16.51		

Table 10 shows the values of the general reliability calculated from the confusion matrices included in Tables 7 and 8, as well as the Kappa index and the correlation coefficient between the reference map of 2013 and the maps generated with logistic regression and neural networks. The map generated by logistic regression has a total reliability of 99.30%, a Kappa index of 0.8913, and a correlation coefficient of 0.8938. These values are higher than those obtained using neural networks by a very narrow margin.

Table 9. Confusion matrix between the map extracted from the 2013 image and the map created by logistic regression (LogReg).

	2013 Map (Reference)			
	Nonimpervious	**Impervious**	**Total**	**Commission Error (%)**
Map 2013 (Reg-Log)				
Nonimpervious	243,838	1493	245,331	0.61
Impervious	285	7572	7857	3.63
Total	244,123	9065	253,188	
Omission error (%)	0.12	16.47		

Table 10. Validation parameters between the map extracted from the 2013 image and the maps created using logistic regression (LogReg) and neural networks (MLP).

	2013 MLP	**2013 Reg-Log**
General reliability (%)	99.29	99.30
Kappa	0.8908	0.8913
R	0.8933	0.8938

3.6. Scenario of Impervious Surfaces to 2030

The scenario calculated for 2030 and its comparison with the existing impervious areas in 2020 is presented in Figure 6. It can be seen that, in the horizon year, important areas to the west of the city will be consolidated; this growth will be facilitated by the existence of access roads, areas with relatively flat relief, as well as the existence of small urban centers. According to this scenario, the impervious surfaces have an area of 51.53 km^2.

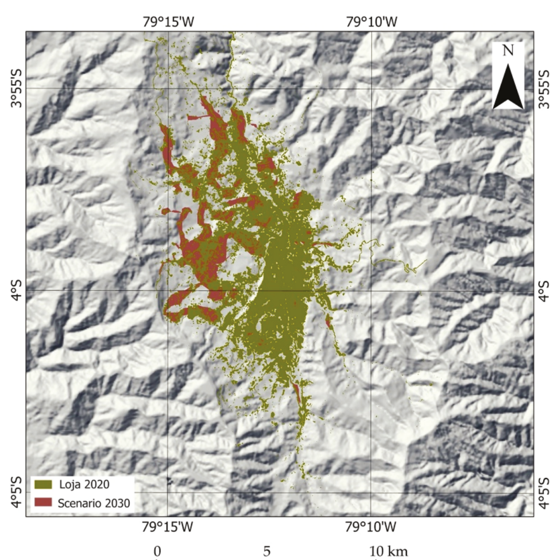

Figure 6. Urban growth scenario for 2030, compared to city size in 2020.

3.7. Hydrological Modeling

The morphological characteristics of the sub-basins are presented in Table 11. It can be observed that the infiltration parameters (CN) undergo an increase as the urban area increases in each sub-basin. This increase is relatively small since, for example, in the Malacatos sub-basin, which has one with the greatest variation in CN, the CN variation reaches a value of around 3%. The variation is small because the urban area in each of the sub-basins is relatively small when compared with their total area. The sub-basins with the largest urban area (Figure 3) present a higher CN value. The concentration time is relatively short since the maximum distance that runoff must travel is related to the slope of the main channel.

Table 11. Characteristics of the sub-basins of the study area.

Sub-Basin	CN				Area (km^2)	tc (h)	tlag (h)
	1989	2001	2013	2020			
Central	95	95	95	95	4.22	0.44	0.27
Jipiro	65.1	65.4	66.2	67	31.93	0.83	0.5
Malacatos	75.3	75.9	77.1	77.3	60.28	1.64	0.99
Norte	76.2	76.9	77.4	77.9	62.57	1.82	1.09
San Cayetano	75.5	77.3	77.3	77.5	5.80	0.47	0.28
Turunuma	74.4	75	76.3	78	24.15	0.9	0.54
Zamora Huayco	65.8	66	66.5	66.2	38.53	1.04	0.62

The precipitation values for different durations and return periods are indicated in Table 12. As expected, the precipitation values increase as the return period and duration increase.

Table 12. Precipitation values associated with each return period.

Duration (min)	Return Periods (Years)			
	10	25	50	100
	Precipitation (mm)			
5	11	12	12.8	15.2
15	21.1	23	24.6	29.2
60	40.9	44.6	47.6	56.5
120	45.4	49.5	52.8	62.7
180	48.3	52.7	56.2	66.7

The storms included in Table 12 applied individually according to the return period, and the state of urban area expansion of the city of Loja allowed obtaining the flows included in Table 13. There is a direct relationship between the return period and the flood flows, as well as between the growth of the urban area and the flood flows for the same return period.

Table 13. Flood flows (m^3/s) for different urbanization states and return periods.

Year	Impervious Surface (km^2)	Return Period			
		10	25	50	100
1989	17.68	100.3	142.4	175.6	290.9
2001	20.18	107.9	151	185.6	304.5
2013	32.87	113.3	162.7	194.45	319.63
2020	43.15	140.3	178.12	208.57	328.71
2030	51.53	157.3	196.78	248.14	360.23

The relationship between flow, return periods, and urban growth is presented in Figure 7, in which a high correlation between the urban area extension and the magnitude of the flows is observed for all different return periods considered.

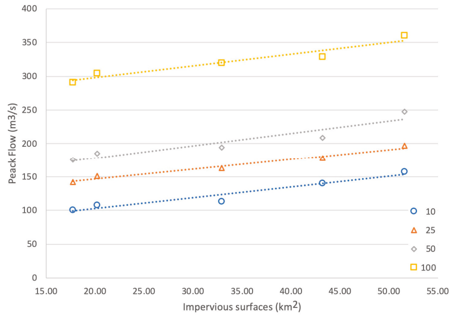

Figure 7. Relationship between flood flow, return periods, and impervious surfaces in the city of Loja.

During the study period, the urban area of the city of Loja experienced a considerable increase, going from 17.68 km^2 in 1989 to 43.15 km^2 in 2020, an increase of 144.12%. The total area of the Zamora River basin is 227.48 km^2, thus in 2020, the city of Loja covered only 18.97% of the total basin, while grasslands, natural forests, and shrubs covered the remaining surface. These land covers can retain surface runoff as they support infiltration, causing an opposite effect to urbanization. This may explain why the increase in flow is moderate despite the significant growth of the city.

3.8. Similarities

The behavior observed in the city of Loja has certain similarities with other urban areas around the world that experienced accelerated growth of impervious areas. Such is the case of the Alto Atoyac river basin (Oaxaca, southern Mexico), which experienced an increase in impervious surfaces of the order of 135 km^2 in the period between 1979 and 2013 [49]. This affected the recharge areas causing a decrease of 2.65 $\times$ 10^6 m^3 of water infiltration into the subsoil. A similar case was observed in Addis Abab (Ethiopia) in the period between 1986 and 2016 [50], in which the impervious surfaces increased by 27%, producing a variation of 4.5 °C in the average surface temperature of the soil. The Pearl River delta in China [51] also experienced a very significant increase in impervious surfaces, from 390 km^2 in 1988 to 4837 km^2 in 2013, with the 1994–1999 period being the one with the fastest growth.

In all the cases mentioned, urban growth is related to a significant increase in the population that extends from cities to suburban areas, affecting soils that were initially covered with grasslands, forests, and agricultural areas. Although each case is different, it is possible to perceive that the increase in impervious surfaces and its effects are present in urban watersheds around the world; therefore, the proposed methodology to generate future scenarios of impervious areas can become a valuable management tool.

4. Conclusions

The NDISI satisfactorily discriminated the impervious areas in the consolidated center of the city, but in the suburban areas, an overestimation of the impervious surfaces was observed, caused by spectral confusion between impervious surfaces and bare soil (product of fallow farms, not very vigorous vegetation, and small newly opened construction areas). On the other hand, the supervised classification of Landsat images presented better discrimination of impervious areas. Therefore, the latter was elected to carry out the study of the spatiotemporal dynamics of soil impermeability in the catchment under study.

A methodology has been proposed that allows modeling future growth scenarios of impervious zones by combining the observed spatiotemporal variability, possible explanatory variables, and logistic regression models.

Slope, elevation, and proximity to highways conditioned urban growth; therefore, there was the persistence of the different land covers in the study area. The best estimate of the change in land cover was found by logistic regression; however, neural networks performed similarly.

There is a direct relationship between the increase of impervious surfaces and the magnitude of flood flows produced by an extreme precipitation event. The basins that experience the greatest growth in impervious surfaces are those that present a greater increase in their flood flows, observing a linear relationship. If the percentage of area covered by impervious surface use is reduced compared with the areas occupied by vegetation in good condition, the increase in flood flows will be moderate.

The urbanization process directly influences the hydrological cycle, increasing impervious surfaces, reducing the infiltration capacity, and increasing the magnitude of flood flows. This must be considered in urban planning.

The increase in impervious surfaces and their effects are present in urban watersheds around the world; therefore, the proposed methodology to generate future scenarios of impervious areas can become a valuable management tool.

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Article

Research on Construction Land Use Benefit and the Coupling Coordination Relationship Based on a Three-Dimensional Frame Model—A Case Study in the Lanzhou-Xining Urban Agglomeration

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Abstract: Coordinating the social, economic, and eco-environmental benefits of construction land use has become the key to the high-quality development of Lanzhou-Xining urban agglomerations (LXUA). Therefore, based on the coupling coordination connotation and interaction mechanism of construction land use benefit (CLUB), we measured the CLUB level and the coupling coordination degree (CCD) between its principal elements in LXUA from 2005 to 2018. Results showed that: (1) The construction land development intensity (CLDI) in the LXUA is generally low, and spatially presents a dual-core structure with Lanzhou and Xining urban areas as the core. (2) The comprehensive construction land use benefit has increased over time, but the overall level is not high. The spatial differentiation is obvious, and the core cities (Lanzhou and Xining) are significantly higher than other cities. (3) The regional differences in the subsystem benefit of construction land use are obvious. The social benefit and economic benefit showed a "convex" shape distribution pattern of "high in the middle and low in the east and west wings", and regional differences of economic benefit vary greatly. The eco-environmental benefit was relatively high, showed a "concave" shape evolution in the east–west direction. (4) In addition, the CCD of the CLUB were still at a medium–low level. The higher the administrative level of the city, the better the economic foundation, and the higher or better the CCD of the social, economic, and eco-environmental benefits. (5) The CCD is inseparable from the influence of the three benefits of construction land use. Therefore, different regions should form their own targeted development paths to promote the coordinated and orderly development of LXUA.

Keywords: construction land development intensity; construction land use benefit; coupling and coordination relationship; spatiotemporal evolution; Lanzhou-Xining urban agglomeration

1. Introduction

Land is the basic carrier of all social and economic activities, and can provide space and resources for human production and life [1]. As an important part of land resources, construction land mainly includes urban construction land, rural residential land, transportation land, water conservancy land, and other construction land. Its utilization is not only related to the development of the secondary and tertiary industries of the national economy, but also has an important impact on the coordinated development of urban and rural areas [2,3]. Land use benefit refers to the comprehensive output of social, economic, and eco-environmental benefits obtained by human capital, labor, and technical input, which is related to the sustainable development of a region [4].

At present, due to rapid global urbanization, most developed countries and regions are striving to complete the simultaneous optimization of land use in society, economy, and ecology, and have made some achievements [5–7]. As the main target of urban expansion in the coming decades [8], driven by industrialization, new urbanization and modernization, the urban population of developing counties has increased rapidly, and the scale of urban construction land development has been expanding continuously. Especially in China, the urbanization rate has increased from 17.90% in 1978 to 59.58% in 2018 [9]. However, with the rapid increase in urbanization level, the contradiction between man and land has become increasingly acute, and problems such as extensive land development and utilization, disorderly expansion, and land pollution have frequently occurred, which has led to an imbalance between social, economic, and eco-environmental benefits of land use, especially in urban agglomeration areas where social and economic activities are more prevalent [10,11]. In addition, urban sprawl will inevitably affect the implementation of cultivated land protection policies and even national food security [12]. Therefore, it is of great significance to study the development intensity and multi-dimensional use benefits of construction land for the rational and optimal allocation of land resources and the sustainable development of urban and rural areas.

Scholars have done a lot of research on land use benefit, mainly focusing on the evaluation of land use benefits, the diversification and applicability of research methods and models, and the excavation of influence mechanisms. In the early days, people only paid attention to the economic benefits of land. For example, the law of land rent in western economics laid a theoretical foundation for the study of the economic benefits of land use [13]. Fulton et al. also verified that urban land expansion was closely related to urban land economic benefits [14]. However, urban sprawl also leads to the increase of social and ecological costs such as prolonged commute time, waste of resources, and destruction of ecological environment pollution [15]. Therefore, while discussing the principle of maximum return brought by non-renewability and restriction of land in principles of land economics, scholars emphasize that land use should meet social goals such as wealth production, fair distribution, and ecological protection; and improve the overall benefit of land use by means of political, legal and economic leverage [16]. With the challenge of sustainable development, people are more aware that the goal of land use is the sustainable use of land resources, which must take into consideration the coordinated development of social, economic and eco-environmental benefits [17,18]. According to previous research, the research object and perspective of land use benefit is not only to evaluate the land use benefit, but also to change the coordination relationship between land use benefit and urbanization and other factors. For example, Zhang et al. analyzed the coupling and coordination between urban land use efficiency and urbanization in 34 prefecture-level cities in the three northeastern provinces, and found that although there is a mutual response relationship between them, urbanization pays too much attention to development speed and despises development quality, resulting in low overall development level and low coupling and coordination degree [19]. He et al. constructed the theoretical framework of land use benefit and industrial structure evolution, and found that industrial structure evolution has an obvious single effect on land use benefit [20].

At the same time, there are regional differences in the study of land use benefits. In developed regions such as America and Europe studies of combined land use, urban expansion, and ecological environment management to try to analyze and evaluate ecosystem services and economic benefits through land use modeling, land protection, and planning behavior [21–23]. While in developing countries, the research is more related to urbanization and urban sprawl, focusing on the rational use of urban land, coordination of urban and rural land, and management strategies for the process of rapid urbanization [24,25]. Research methods and models of land use benefits are also hot topics that scholars pay attention to. The existing research is mainly based on the construction of a land use benefits index system, with the data envelopment analysis model, neural network model, multi-objective linear programming model, SWAT model, coupling degree model, and other methods [26–30]. With the development of science and technology, GIS, remote sensing and spatial measurement methods have been introduced into the study of land use and land expansion, and the spatial monitoring and analysis functions of these methods have been applied to realize the visual expression of the research results [31,32]. Of course, due to data availability and the research objects being different, the weighting methods and indicators selected are also different. Methods such as the analytic hierarchy process (AHP), coefficient of variation method, expert scoring method, and entropy weight method are widely used [33–35]. Based on this, Ran et al. used the Friedman chi-square test, Spearman correlation, consistency test, and one-way analysis of variance to compare different subjective and objective weighting methods, they found that the comprehensive index method, rank-sum ratio method, entropy method, and the integrated entropy methods all have significant statistical characteristics, and each has its own advantages and disadvantages. A more scientific, comprehensive approach is required [36]. Research on the influencing factors of land use benefits generally focuses on economic, social, transportation, and political factors [37–40]. Some studies have also found that the determinants are related to urbanization and industrialization, accessibility, and economic transformation [41,42]. These studies provide policy and guidance for improving land use efficiency and promoting sustainable development of cities.

From the current research progress, we also find that most of the land use benefits studies focus on the desirable outputs of limited land use, such as economic benefit, while there are few studies on undesirable outputs such as pollution and industrial emissions from land use. In addition, the study areas are mainly concentrated in areas with a high economic level, while the research on land use benefits of the northwest region China, where the ecological environment is relatively fragile, is relatively weak. Therefore, this paper selects the LXUA which is the important urban agglomeration on the Silk Road Economic Belt as an example. On the basis of elaborating and analyzing the connotation and mechanism of the coupling coordination of multi-functional benefits of construction land use, a three-dimensional framework system of CLUB is constructed including society, economy, and eco-environment. Secondly, using an entropy method, a composite index model and coupling model, and the application of CLUB is demonstrated. Finally, according to the evolution law and spatial differentiation characteristics of the coupling coordination relationship of CLUB in different regions, an optimization strategy for sustainable land use development is proposed according to local conditions. The overall workflow of the study is shown in Figure 1.

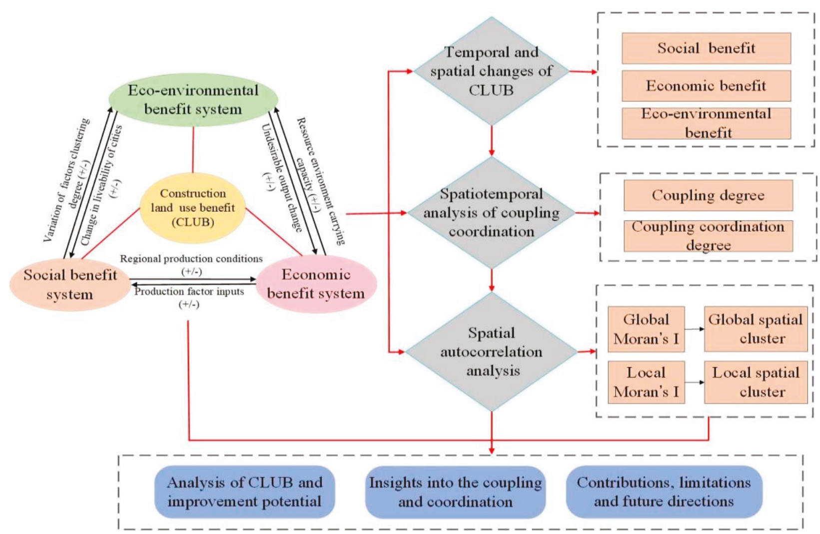

Figure 1. The coupling interaction relationship of the CLUB system and workflow of the study.

The structure of this article is as follows. Section 2 explains the conceptual framework of the interactive coupling relationship of the CLUB system. Section 3 introduces the current situation of LXUA, data sources, and the research method. Section 4 analyzes the spatiotemporal differentiation of the CLUB based on the CLDI, and explores the coupling and coordination relationship between the social, economic, and eco-environmental benefits of the construction land use. Section 5 discusses and analyzes the important conclusions. Section 6 summarizes the main conclusions and future research directions.

2. Interaction Coupling Mechanism of CLUB

The economic, social, and eco-environmental benefits of construction land use are closely related, restricted, and promoted by each other [43]. On one hand, land is an important carrier of all human activities. With the rapid advancement of urbanization, construction land has been continuously developed and utilized, providing space and resources for various activities. Its quantity and quality are closely related to the social and economic benefits. If people develop land and do not exceed the resource's environmental carrying capacity, we can get economic benefit continuously. If the economic benefit is invested in improving people's livelihood and infrastructure construction, good social benefit will be produced. The improvement of social benefit will improve regional production conditions, promote further development of the regional eco-environment. On the other hand, in the process of land use, due to the limitation of technology, capital, and knowledge level, people will have negative economic scale effects, which can lead to environmental pollution, ecological systems destruction, and affect the eco-environmental benefit of land. The destruction of the eco-environment will worsen the local environmental conditions and affect the social benefit of land use. Moreover, it will also reduce the local resources environmental carrying capacity, resulting in the loss of land economic benefit. To sum up, only when the three achieve dynamic coordination and balance, can they promote the effective improvement of the whole system benefits to a greater extent and maximize the benefits (Figure 1).

3. Materials and Methods

3.1. Study Area

The LXUA is a 9.75×10^4 km regional urban agglomeration in the upper reaches of the Yellow River in the inland northwest China (Figure 2), including nine cities, Lanzhou, Baiyin, Dingxi, Linxia, Xining, Haidong, Hainan, Haibei, and Huangnan, and a total of 39 counties. The population concentration degree is relatively high, and it is an important radiation center and growth pole in Northwest China. As of 2018, the GDP of the LXUA reached CNY 515.59 billion, accounting for 51.13% of the total of Gansu and Qinghai province. As the hub of the Silk Road Economic Belt and the Yangtze River Economic Belt, LXUA's geographical advantages have become increasingly prominent, especially the construction of the new land–sea passage in the west, which makes LXUA's hub position of the "Sixth Ring in the Middle" more prominent. This region has good resource endowment and belongs to a region with good soil–water combination conditions in Northwest China. However, the economic level within the urban agglomeration varies greatly, and the imbalance of regional development is outstanding. Therefore, under the background of the new round of western development, how to balance the benefit relationship between land use, promote the coordination between development, utilization and protection of land, and realize the promotion of comprehensive benefit of land use in the region, has become the primary task of high-quality development of urban agglomerations.

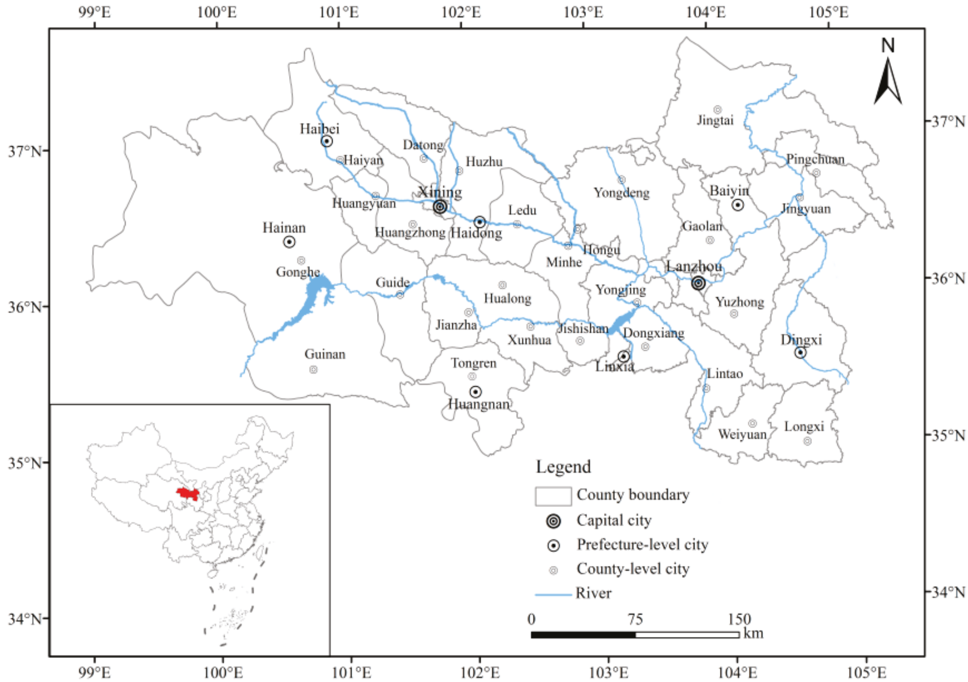

Figure 2. Study area.

3.2. Data Sources

This research takes 39 counties in LXUA as the basic research unit. The vector boundaries of urban agglomerations and the construction land data are all from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn accessed on 15 November 2021). According to the national county-level land use classification system, the data of the corresponding year was revised to extract and divide the construction land area data of each county. The socioeconomic data of each research unit was mainly derived from the Statistical Yearbooks of the Chinese County, Statistical Yearbooks of Gansu and Qinghai Province. The eco-environmental data was mainly derived from the environmental protection bureaus of cities and prefectures and field survey.

3.3. Methods

3.3.1. CLDI Measurement

Development intensity can be used to measure the extent of land development and utilization by human activities in a certain region. As for the development intensity, 20% is generally regarded as the standard line of livability and 30% as the warning line, globally. The National Land Planning Outline (2016–2030) proposes that the development intensity of China's land should not exceed 4.62%. This paper selects the proportion of construction land area to the regional total area proposed by Fan in the main functional zone as a measure of CLDI [44]. The equation is as follows:

$$\text{CLDI} = \frac{CLA}{TA} \times 100\% \tag{1}$$

In Equation (1), CLDI represents construction land development intensity, *CLA* is construction land area, and *TA* is the total area of region.

3.3.2. CLUB Index System

The CLUB mainly refers to the comprehensive output of social, economic, and eco-environmental benefits caused by the labor, capital, and technology invested by human beings in construction land. Therefore, drawing on previous studies [43,45,46], and combined with the connotation of CLUB and the scientific principle of index selection, and the availability of data, this paper constructed a three-dimensional evaluation index system including social, economic, and eco-environmental benefits (Table 1).

Table 1. Three-dimensional framework evaluation index system of CLUB.

Criterion Layer	Indicator Layer	Attribute	Weight
Social benefits	Urbanization level (%)	+	0.0534
	Population density per unit construction land area (person/km^2)	+	0.0646
	Resident per capita net income (RMB/person)	+	0.0511
	Employed persons per land (person 10,000/km^2)	+	0.0469
	Per capita road area (m^2/person)	+	0.0812
Economic benefits	GDP per unit area (RMB 10,000/km^2)	+	0.2377
	Fiscal revenue per unit of construction land area (RMB 10,000/km^2)	+	0.0683
	GDP per unit construction land area of secondary and tertiary industries (RMB 10,000/km^2)	+	0.0625
	Retail sales of consumer goods per unit of construction land area (RMB 10,000/km^2)	+	0.0769
	Investment in fixed assets per unit construction land area (RMB 10,000/km^2)	+	0.0593
Eco-environmental benefits	Green space coverage in built-up areas (%)	+	0.0373
	Public green space per capita (m^2/person)	+	0.0506
	Discharge of industrial wastewater per unit construction land area (T/km^2)	-	0.0368
	Industrial waste gas emissions per unit construction land area (T/km^2)	-	0.0335
	Discharge of industrial solid waste per unit construction land area (T/km^2)	-	0.0399

3.3.3. CLUB Index Weight Setting and Score Calculation

Data Preprocessing

Different indicators have positive and negative effects, in order to ensure the rationality of the evaluation results, it was necessary to standardize the data to ensure the uniformity of the dimensions of each indicator by the following:

$$x'_{ij} = \begin{cases} \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} & \text{Positive indicator} \\ \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} & \text{Negative indicator} \end{cases} \quad (2)$$

In Equation (2), x'_{ij} represents the standardized value, x_{ij} is the original data value of the j-th indicator, $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the j-th indicator.

Weight Calculation

Due to the different degrees of dispersion of different indicators, the impact on the comprehensive evaluation is also different. Therefore, this study used the more objective entropy method to calculate the index weight [46,47]. The weight results are shown in Table 1.

Comprehensive Value and Subsystem Score Calculation

According to the above standardized values and weights, the social benefit value (U_{soc}), economic benefit value (U_{eco}), and eco-environmental benefit value (U_{env}) of construction land use were calculated in combination with the composite index method [46]. Then, the comprehensive value (U_{com}) of construction land use of the i-th sample was obtained by using the weighted evaluation method of the criterion layer.

$$U_{soc/eco/env} = \sum_{j=1}^{n} (w_j \times x'_{ij}) \quad (3)$$

$$U_{com} = \alpha U_{soc} + \beta U_{eco} + \gamma U_{env} \quad (4)$$

In Equations (3) and (4), U_{soc}, U_{eco}, and U_{env} represent the social benefit, economic benefit, and eco-environmental benefit of construction land use, respectively; x'_{ij} is the standard value of the *j*-th index in three systems; w_j represents the weight of the corresponding index. U_{com} represents the comprehensive benefit of construction land use. α, β, and γ are undetermined coefficients, which represent the importance of the social, economic, and eco-environmental benefits of construction land use, respectively. Because the three need to coordinate and advance together and are almost equally important, this paper takes $\alpha = \beta = \gamma = 1/3$.

3.3.4. Coupling Degree (CD) and Coupling Coordination Degree (CCD)

Coupling is usually used to describe the degree to which two or more systems interact and affect each other [48,49]. This paper constructs a CD model among the three-dimensional benefits of social, economic, and eco-environmental. Based on the CD, this paper further draws on the CCD to measure the degree of harmony and consistency of the social, economic, and eco-environmental benefits of construction land use in the process of change [50]. The equations are as follows:

$$C = \left[\frac{U_{eco} \times U_{soc} \times U_{env}}{\left(\frac{U_{eco} + U_{soc} + U_{env}}{3} \right)^3} \right]^{\frac{1}{3}} \tag{5}$$

$$D = \sqrt{C \times U_{com}} \tag{6}$$

In Equations (5) and (6), C denotes the coupling degree of social, economic, and eco-environmental benefits of construction land use, and $C \in [0, 1]$. D denotes the coupling coordination degree between social, economic, and eco-environmental benefits of construction land use, and $D \in [0, 1]$. The larger the D, the higher the CCD. When $C = 0$, the CD is extremely low, and the systems, or between elements within the system, are in a disordered state. When $C = 1$, the CD is the largest, and benign coordinated coupling is achieved between systems or between internal elements of the system.

On the basis of existing research, we found that many scholars have used the critical value method to classify CD and CCD. However, this paper does not subjectively carry out quantitative division, but chooses the objective quartile method. The CD and CCD are divided into four stages from low to high level: lower level, medium level, higher level, and benign (optimal) level.

4. Results

4.1. Spatiotemporal Change of CLDI

According to Equation (1), it was found that the CLDI in LXUA had an upward trend from 2005 to 2018. The average of CLDI in 2005, 2010, and 2018 were 6.53%, 7.31% and 8.54%, respectively. In 2005, CLDI was dominated by low-value and lower-value counties, accounting for 38.46% and 23.08%, respectively. In 2010, the CLDI showed a steady increase, compared with 2005, the proportion of low-value areas decreased, and the number of medium and high-value areas increased. By 2018, the CLDI showed an accelerating trend, the number of counties with a development intensity of 2% and above continued to increase. However, compared with cities in eastern and central China [31], the CLDI in LXUA is relatively low.

As shown in Figure 3, the CLDI differs on different spatial scales. On the provincial scale, the CLDI in Gansu area (8.63%) is higher than that in the Qinghai area (6.95%). On the prefecture-level city scale, Xining, Lanzhou, and Baiyin ranked the top three in terms of development intensity. At the county level, the CLDI in the municipal districts of Xining, Linxia, Lanzhou, and Baiyin all exceeded the national land development intensity of 4.60% in the National Land Planning Outline (2016–2030). In terms of changes in the entire urban agglomeration, the CLDI in the LXUA generally presents a "core-periphery" spatial structure with the Lanzhou and Xining urban areas as the core, and other peripheral areas decreasing in turn. The closer it is to the city center, the stronger the gathering capacity of construction land and the larger the development scale. On the contrary, the further from the city edge, the CLDI gradually decreases.

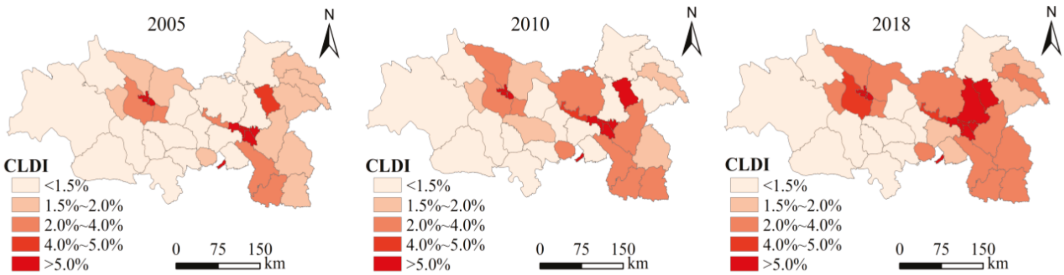

Figure 3. The spatial pattern of CLDI in LXUA.

4.2. Spatiotemporal Change of CLUB

As shown in Figure 4a, the social benefit of construction land use showed a trend of "first rise and then decline", and first rose from 0.28 in 2005 to 0.35 in 2010, and then declined to 0.33 in 2018. From Figure 4b, the variation coefficient of social benefit fell from 0.57 to 0.44, a decrease of 22.81%, which indicates that the regional differences of social benefit tend to narrow. From Figure 5a, the social benefit is characterized by a "convex" shaped spatial distribution. The social benefit of Lanzhou and Xining was always higher than that of other regions. Among them, the middle and high value regions are gradually concentrated in the central area connected with Lanzhou and Xining, while the social benefit in the peripheral counties of the urban agglomeration is low.

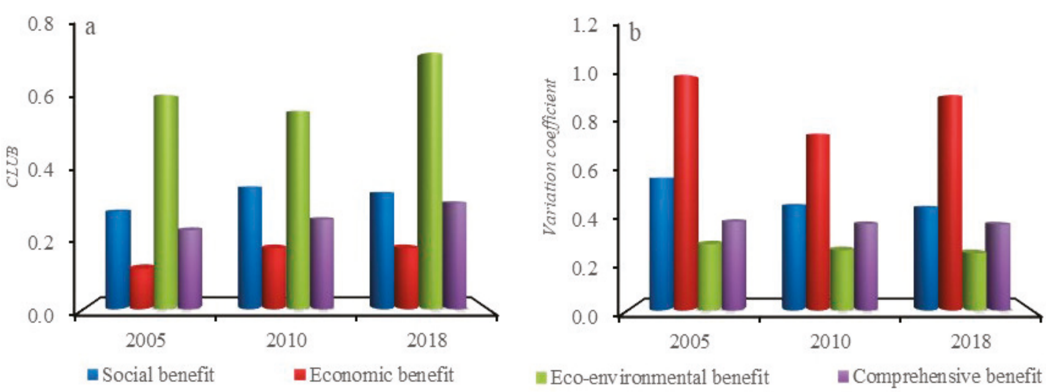

Figure 4. CLUB value and its variation coefficient. (**a**) Construction land use benefit level, (**b**) Variation coefficient of construction land use benefit.

As shown in Figure 4a, the economic benefit of construction land use from 2005 to 2018 showed a "continuous increase", and increased from 0.12 to 0.17, an increase of 41.67%. However, as can be seen in Figure 4b, the variation coefficient of economic benefit decreased from 1.01 to 0.93, with a small reduction of only 7.92%, which means that the regional differences of economic benefit were still large. From Figure 5b, the economic benefit presented a spatial pattern of "high in the west and low in the east, high in the middle and low on the outside". The middle and high value areas were concentrated in Huangzhong, Chengguan, and Ledu, and the low value areas were mainly distributed in the eastern fringe counties of the urban agglomeration.

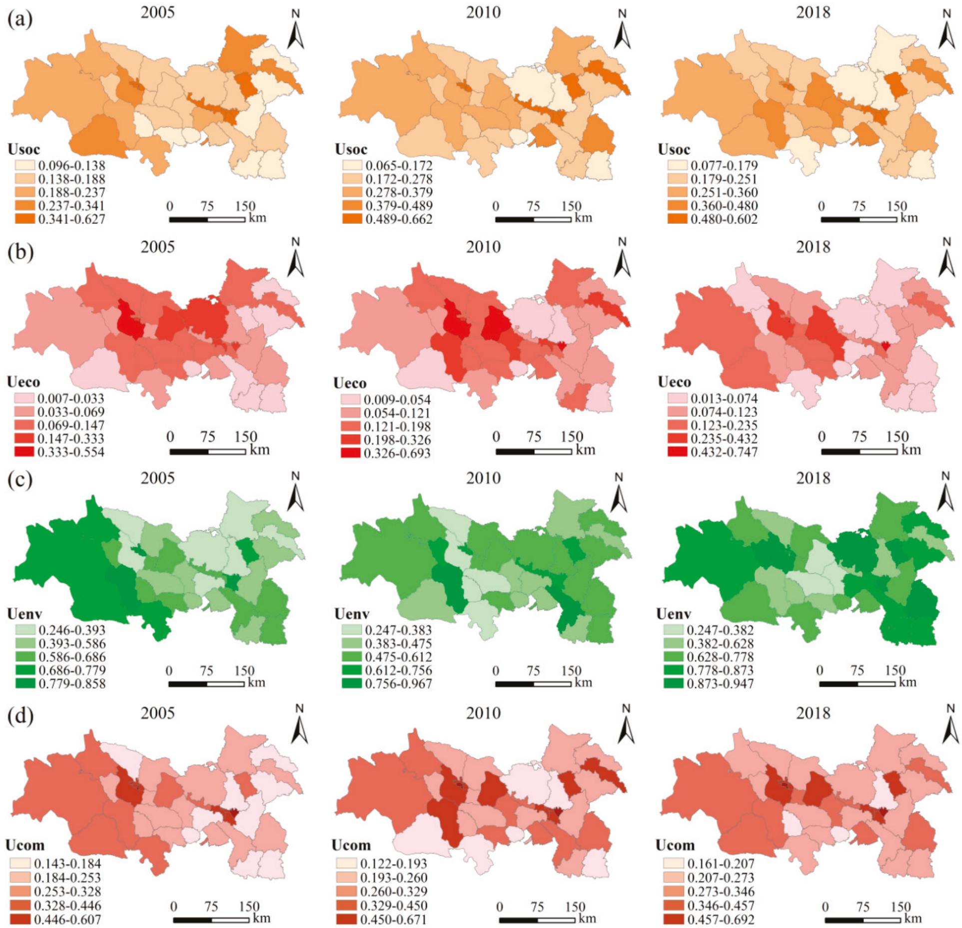

Figure 5. Spatial pattern of the CLUB in LXUA. (**a**) Social benefit, (**b**) Economic benefit, (**c**) Eco-environmental benefit, (**d**) Comprehensive benefit.

From Figure 4a, the eco-environmental benefit of construction land use showed a characteristic of "first decline and then increase". Itfirst declined from 0.61 in 2005 to 0.57 in 2010, and then increased to 0.73 in 2018. From Figure 4b, the regional differences of the eco-environmental benefit were smaller and tended to shrink slightly, with a shrinking rate of 10.71%. As can be seen in Figure 5c, the eco-environmental benefits were characterized by a "concave" shaped spatial distribution. In 2005, the high value areas were mainly concentrated in the western region. By 2018, the eco-environmental benefit of the eastern of the urban agglomeration had risen significantly, and showed a trend of "retreat from west to east".

As shown in Figure 4a, the comprehensive benefit was a continuous upward trend during the study period, and increased from 0.27 to 0.32, an increase of 18.52%. However, we can see from Figure 4b the variation coefficient of comprehensive benefit decreased from 0.38 to 0.37, with a decrease of only 2.63%, which indicates that the regional differences of comprehensive benefit demonstrated only a slight shrinking trend. From Figure 5d, the comprehensive benefit showed a distribution of "high in the middle and low in the outside", and the urban land use benefit with Lanzhou and Xining as the core were always higher than that of other counties. At the same time, the number of low-level counties decreased significantly, from 20.52% to 7.69%. Overall, the CLUB of LXUA are mainly at low and lower level, and showed a sequential shift from low level area to lower level area.

4.3. Coupling and Coordination Analysis of CLUB

During the important period of socio-economic transformation and development of LXUA from 2005 to 2018, its land development, utilization structure, and output benefits were affected by population agglomeration, industrial development, and urban policies. As shown in Figure 6a, the coupling degree (CD) value C of CLUB generally fluctuated and rose, and the western counties were higher than the eastern counties. Higher and benign level counties of the CD gradually shifted from a scattered to centralized distribution, mainly in the western and central areas of the urban agglomeration. As the "back garden" of the central city, the demand for industrial development, infrastructure, and residential space in such areas may be in a stage of continuous increase, coupled with the strong promotion of the policy of linking the increase and decrease of construction land, which made the social, economic, and comprehensive benefits of construction land at a good level. Therefore, the CD is also high. Lower level counties of the CD were concentrated in the eastern and northern fringes of LXUA. Such areas were mostly development areas of traditional industry with slow economic development and a single structure, with primary industry accounting for a considerable proportion. Its low level of urbanization and industrialization, limited population agglomeration capacity, and slow expansion of built-up areas, resulted in social, economic, and comprehensive benefits of construction land use being low. Therefore, the CD is also lower.

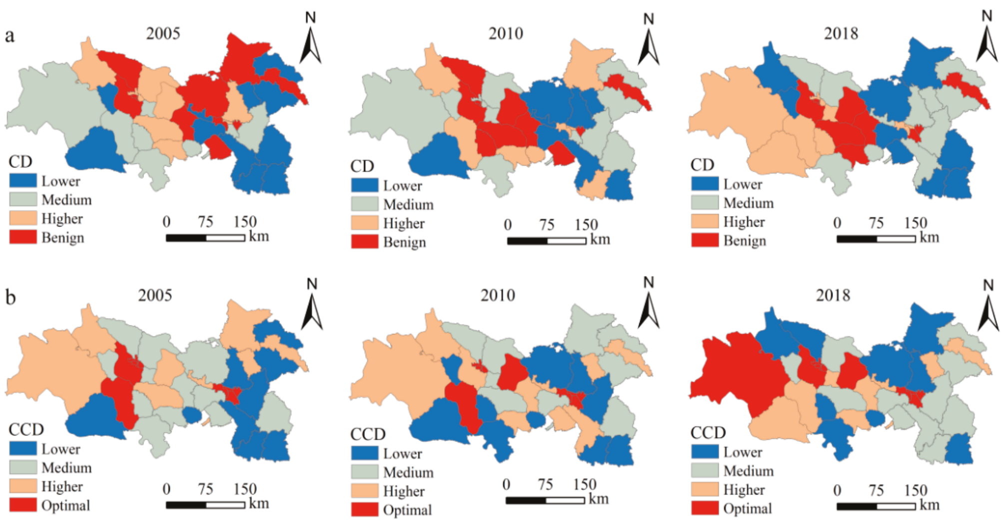

Figure 6. Spatial differentiation of the CD and CCD of social, economic, and eco-environmental benefits of construction land use in LXUA. (**a**) Coupling degree, (**b**) Coupling coordination degree.

To judge whether the input and output of regional construction land development is reasonable and orderly, in addition to considering its interaction and correlation, it is also necessary to explore the coupling coordination degree (CCD) of CLUB. Figure 6b showed that the spatial pattern of the CCD was basically consistent with the CD, but the CCD was generally lower than the CD. In Yongdeng, Gaolan, Jingtai, Yuzhong, Anding, Longxi, Haiyan, and Huangyuan counties, where the CD was at a medium-low level, their coupling characteristics showed a low-level orderly coordination state, and the CLUB in such areas was at a lower level of coordinated evolution, and the industrial development was mostly in the primary stage, so the response sensitivity to the improvement of construction land use efficiency was slow. Correspondingly, the CCD of higher CD regions of construction land use benefit was also higher, which reflects a high-level synchronous evolution state. From the spatiotemporal evolution, the CCD showed a continuous upward trend, and a regional distribution with optimal level coordination stages did not change significantly from 2005 to 2018, and was mainly concentrated in Lanzhou and Xining urban areas. The medium and lower level counties accounted for 41.03% in 2018. Overall, the CCD between the social, economic, and eco-environmental benefits of construction land use in LXUA is still in the lower level coordination stage, and the CCD needs to be improved urgently.

4.4. Spatial Autocorrelation Analysis

Spatial autocorrelation can well express the spatial relationship of CCD between the CLUB, so as to further reveal the spatial connections and differences among the research units [50]. Figure 7 shows the Moran's I of the CCD from 2005 to 2018. The Moran's I values are all positive, and $p < 0.01$, which indicates that the CCD had a significant positive spatial autocorrelation. The Moran's I showed a fluctuating trend. From 2005 to 2010, the Moran's I had a decreasing trend, indicating that the spatial agglomeration of the CCD was weakened. From 2010 to 2018, the Moran's I had a slowly increasing trend, indicating that the spatial agglomeration of CCD was slowly increasing.

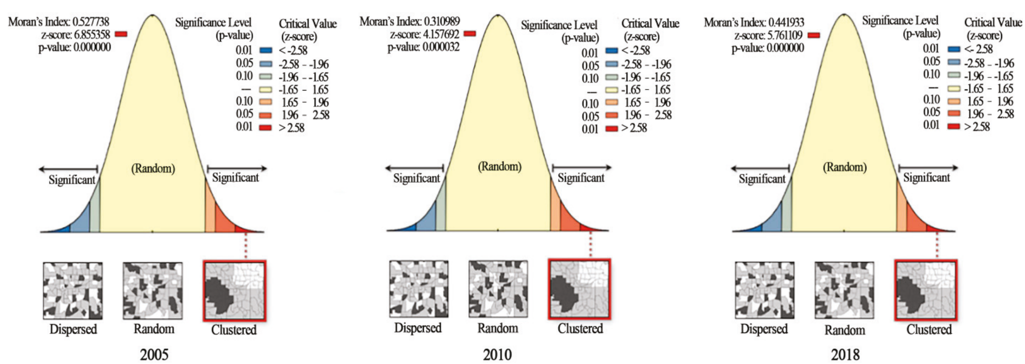

Figure 7. Spatial agglomeration of the CCD of CLUB from 2005 to 2018.

In addition, local Moran's I was used to reveal the spatial association type of CCD, and was visualized in ArcGIS 10.6 (Figure 8). In 2005, 2010, and 2018, the spatial distribution of the high–high cluster was basically the same, mainly in the Xining urban area and some surrounding counties. Low–low clusters were mainly distributed in Longxi, Weiyuan, Tongren, and Xunhua. The spatial distribution of the two categories of spatial outliers that were statistically significant (high–low and low–high outliers) was fragmented.

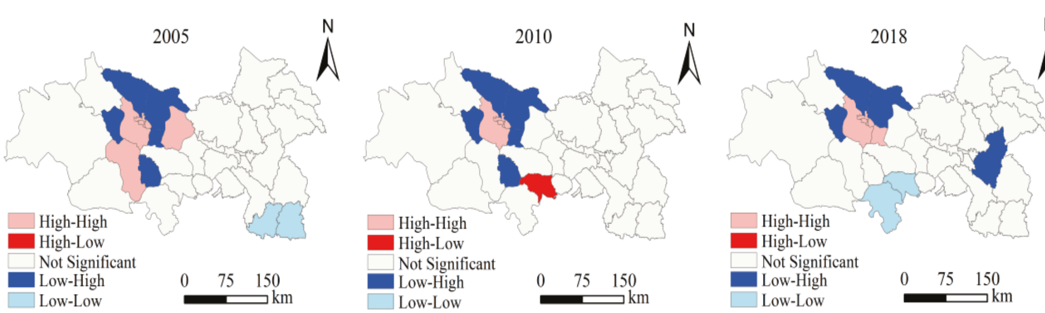

Figure 8. Spatial correlation type diagram of CCD of CLUB in the LXUA.

5. Discussion

5.1. Reasons for the Change of CLUB and CCD Relationship

The evaluation of CLUB is conducive to promoting the intensive and efficient use of land resources and the sustainable development of the region, especially for the northwest region where the ecological environment is relatively fragile. As an important ecological barrier support area in western China, LXUA plays a key role in promoting the high-quality development of the Yellow River Basin, promoting the development of the western region, and ensuring the ecological security of Northwest China [51,52]. The research results show that the CLUB of LXUA is generally low, the polarization of difference is obvious, and the regional development imbalance is a prominent problem. This is consistent with the findings of Shi et al. [53]. Especially, there are significant regional differences in the social and economic benefits. The lack of long-term spatial control measures made Lanzhou and Xining the dominant places. The excessive agglomeration of low-level urban functions, and the limited radiation effect of polarized regions restrict the urban agglomerations integration as well as balanced economic development. In addition, the CCD among the social, economic, and eco-environmental benefit of construction land use increased from 0.48 to 0.55, and is still at a medium and low level coordination stage, which is also consistent with previous research [54–56]. However, the northwest region is currently in a stage of accelerated urbanization. The rapid population growth in some areas has increased the development of land resources. At the same time, the economic structure of the counties is similar, the industrial level is relatively low, and there are still many traditional industries with high input, consumption, and emissions. Coupled with the fragile ecological background and increasing resources, environmental pressure caused most counties to be assessed as lower level regions. This unsustainable development mode needs to be alleviated urgently.

5.2. Suggestions for Promoting the CCD of CLUB

With the promotion of ecological civilization construction and the transformation of new urbanization development, combined with the research results of this paper, it has become an inevitable choice for the future land use of LXUA to promote the coordinated development of the social, economic, and eco-environmental benefits. In this process, different types of regions should form their own targeted development paths. For lower-level coordination areas, they should first transform and upgrade the industrial structure to achieve the mutual assistance of urban functions, the industrial dislocation layout, and industrial chain linkage close development, to enhance the economic benefit of land and improve its social and eco-environmental benefits, promote the harmonious and orderly development of construction land in society, economy, and ecology. For medium coordinated regions they should rely on local characteristic industries and regional advantages to first achieve healthy economic development, thereby increasing investment in the construction of basic, urban public services and other facilities, and to promote the improvement of the social benefit of construction land use, so as to improve the overall CCD of such areas. For higher coordination regions, they should strengthen the construction of resource-based industries to continue industrial transformation, and promote the orderly development of the cities, and the development of green, efficient, clean production, and a circular economy. The optimal coordination areas such as Lanzhou and Xining should take the opportunity of the new round of western revitalization to strengthen the intensive use of construction land and improve the infrastructure construction level to accelerate the transformation and upgrading of traditional advantageous industries, to increase the proportion of the tertiary industry, and to consolidate the industrial foundation and employment support for urban development, so that the urban population capacity can be improved, and realize the transformation of the multi-functional benefits of construction land utilization a at a more highly coordinated level.

6. Conclusions

This paper uses panel data of 39 county-level cities of the LXUA in China from 2005 to 2018 to construct a three-dimensional system of CLUB, covering society, economy, and eco- environment. We analyzed the temporal and spatial evolution characteristics of CLDI and CLUB and explored the coupling coordination relationship among the benefits. The main conclusions are as follows: (1) The CLDI generally presents a dual-core spatial distribution with Lanzhou and Xining urban areas as the core. In the center of the city, the CLDI is greater. In contrast, in the edge cities, as the distance increases, the CLDI gradually decreases. (2) The social benefit of construction land use showed a "convex"-shaped spatial distribution pattern of "high in the middle and low in the east and west wings". The economic benefit was basically the same as the social benefit in terms of spatial distribution, with great regional differences. The eco-environmental benefit was relatively high andregional differences were small. (3) The comprehensive benefit construction land use had significant spatial differences, and generally presented a gradient spatial structure of "core cities > node cities > general county towns", and the comprehensive benefit was mainly lower level and low level. (4) From 2005 to 2018, the interaction between the social, economic, and eco-environmental benefits of construction land use developed in a coordinated direction in terms of time evolution and spatial correlation, but generally the CCD was still at a medium-low level, and the spatial clustering features were significant.

This paper conducts a more comprehensive analysis of the spatiotemporal evolution of CLDI, CLUB, and the coupling coordination relationship of the multi-functional use benefits of construction land in LXUA, which is of great significance to the sustainable development of future land use of different types. However, there are still some deficiencies that need to be pointed out: (1) Based on the availability of county data, the selection of indicator systems still can be improved. (2) With the update of technical means such as big data, the "flow" element is becoming more and more important. However, this paper does not consider the impact of "data flow" and "feature flow" on regions. (3) Compared with other studies [57–59], this study lacks consideration of more refined data and techniques, and impact mechanisms. In the future, on the basis of comparing and learning from the more mature urban agglomeration paths, a more in-depth analysis and research should be carried out in combination with the characteristics of the study area and the shortcomings of this paper.

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Abbreviations

LXUA	Lanzhou-Xining urban agglomerations
CLDI	Construction land development intensity
CLUB	Construction land use benefit
CD	Coupling degree
CCD	Coupling coordination degree.

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Downscaling Switzerland Land Use/Land Cover Data Using Nearest Neighbors and an Expert System

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Abstract: High spatial and thematic resolution of Land Use/Cover (LU/LC) maps are central for accurate watershed analyses, improved species, and habitat distribution modeling as well as ecosystem services assessment, robust assessments of LU/LC changes, and calculation of indices. Downscaled LU/LC maps for Switzerland were obtained for three time periods by blending two inputs: the Swiss topographic base map at a 1:25,000 scale and the national LU/LC statistics obtained from aerial photointerpretation on a 100 m regular lattice of points. The spatial resolution of the resulting LU/LC map was improved by a factor of 16 to reach a resolution of 25 m, while the thematic resolution was increased from 29 (in the base map) to 62 land use categories. The method combines a simple inverse distance spatial weighting of 36 nearest neighbors' information and an expert system of correspondence between input base map categories and possible output LU/LC types. The developed algorithm, written in Python, reads and writes gridded layers of more than 64 million pixels. Given the size of the analyzed area, a High-Performance Computing (HPC) cluster was used to parallelize the data and the analysis and to obtain results more efficiently. The method presented in this study is a generalizable approach that can be used to downscale different types of geographic information.

Keywords: land cover; land use change; downscaling approach; Switzerland; geographic information system; aerial photo interpretation; topographic map; inverse distance weighting; expert system

1. Introduction

1.1. Pressures on Land Resources in Switzerland

The Swiss Federal Department of Environment, Transport, Energy and Communications (DETEC) in its 2016 Strategy stated that by 2030, Switzerland is aiming at becoming a sustainable country while remaining an attractive and competitive business location with a high quality of life [1]. This ambitious objective is presently challenged by several trends such as population growth, increased mobility, energy demand, high consumption of resources, urbanization, loss of biodiversity and associated ecosystem services, and the digitalization of society along with related big data [2]. These trends have an important impact on the environment. Therefore, protecting the environment is a central mission for the Swiss Government, who wants to promote and adopt more sustainable approaches for the exploitation of natural resources [3]. To this end, actions such as protecting natural resources, improving urban planning, reducing emissions of greenhouse gases, preserving water quality, retaining biodiversity and ecosystem services, protecting soils, and preserving countryside are essential [4–6].

All these trends are also placing unprecedented demands on land. Between 1985 and 2009, 15% of the country's surface area changed [7]. Settlement and urban areas have expanded, agricultural areas have been lost, forested areas have increased, and glaciers have receded [8–10]. During the last 50 years, it is estimated that human activities have affected globally about 83% of the terrestrial land surface and have degraded about 60% of services provided by ecosystems. Land degradation is now at a critical point and will undermine the well-being of 3.2 billion people by 2050 [11]. Consequently, Land Cover (LC) and Land Use (LU) changes are considered as a major tangible indicator of the human footprint [12].

To preserve its potential to deliver goods and services, land should be efficiently and sustainably managed. National policies such as the Green Economy, the Spatial Planning Act, the Spatial Strategy for Switzerland, the Sustainable Development Strategy 2016–2019, or the Strategy on Biodiversity are essential components to support this vision [13]. They generally acknowledge that a given area of land can offer many environmental, social, cultural, and economic benefits at once. However, most ecosystems are being degraded by unsustainable exploitation, fragmentation, urban growth and development of transport, and energy networks. This reduces the spatial and functional coherence of the landscape and consequently, degraded ecosystems are unable to provide the same services as healthy ecosystems [14].

Detailed and accurate knowledge on Land Use and Land Cover Change (LU/LCC) is crucial for many scientific and operational applications, such as watershed analyses [15,16], land use impact on stream ecology [17–19], species and habitat distribution modeling [20], dynamic modeling of species migration [21,22], reserve site selection [23], impact assessment on biodiversity [24], land use planning [25], or monitoring of land use changes [26]. LU/LC affects many aspects of policy and decision-making processes related to climate, water, biodiversity, ecosystems, agriculture, or disasters. Additionally, LU/LCC assessment also contributes to many Multilateral Environmental Agreements (MEAs) and Global Environmental Goals (GEGs) to guide and assess progress toward policy outcomes [27,28]. The importance of sustainable management of land resources is recognized in regional and global policies such as the 2030 Agenda for Sustainable Development, which contains land-related targets and indicators under 14 out of the 17 Sustainable Development Goals (SDGs) [29–31]. Many land organizations and stakeholders are committed to fully implement the SDGs and to monitor the land-related indicators to promote responsible land governance. Land is a significant resource for many sectors; timely and high-resolution LU/LC data therefore constitute critical information for the achievement of the SDGs [32]. Accurate and up-to-date LU/LCC information and related changes are also the base of a sustainable development assessment [33] based on structural (both temporal and spatial) and functional (social, ecological, economical) attributes of the landscape [34]. A supplementary challenge is represented by the spatial scale at which the assessment is performed. For each problem under study, an appropriate scale must be identified, especially when relating ecological processes to landscape patterns [35].

1.2. Land Use/Land Cover Data in Switzerland

LU/LCC is increasingly acknowledged as both a driver and a consequence of climate and biodiversity changes [36–38]. This important role has been featured by the fact that land cover is considered as an Essential Climate Variable (ECV), a supplementary Essential Water Variable (EWV), and a candidate Essential Biodiversity Variable (EBV) [39–42]. LU/LCC affects the biophysics, biogeochemistry, and biogeography of both the atmosphere and biosphere, with important consequences for human well-being. Consequently, accurate and timely information is necessary for understanding the impact of LU/LCC variations on the structure and functioning of ecosystems, as well as provision, support and regulation of goods and services [29,43,44]. However, it is recognized that inadequate information on LU/LC and its change over time is a recurrent and common problem that prevents policymakers from making sound, informed decisions [27,45–47]. Currently, the official LU/LC information in Switzerland (Arealstatistik) is updated approximately every 6 to 8 years and derived by visual interpretation of aerial photographs where an LC and an

LU category are assigned to each intersection point of a regular 100 m grid [8]. Although this data set is very useful thanks to its thematic richness, neither its low spatial resolution nor the update frequency allow for providing accurate and timely information to depict and understand the dynamic of LU/LCC and the related impact across the country [48,49]. Accurate LU/LC change assessment and effective LU/LCC projections require higher spatial (e.g., 30 m) and temporal (e.g., yearly) data products to build consistent time series [47,50].

1.3. Downscaling as a Possible Approach for High-Resolution LU/LC Data

Besides traditional remote sensing approaches, such as unsupervised, supervised, or object-based classifications [51–54], more advanced techniques include machine or deep learning [55–58], new sensors with higher spatial and spectral resolution such as Sentinel-2 [59,60], and automated procedures to reduce the time-consuming process of manual verification of data [61,62]; a possible alternative to generate high-resolution LU/LCC data [63] is represented by downscaling techniques [64]. In many disciplines, downscaling is used to derive local scale maps from information available at coarser resolution. Climatologists refer to statistical downscaling [65] to describe this general approach that has been widely used not only for temperature and precipitation information [66,67] but also for wind speed [68] and air humidity [69]. In turn, downscaled climatic information is used in many different applications, such as hydrological modeling [70–72], species distribution modeling [73], and geological risk assessments [74]. However, downscaling of LU/LCC data is not very common and has not been widely applied [64,75,76].

Several statistical approaches have been used for downscaling. For instance, Barodssy et al. [77] used fuzzy rule-based models to predict frequency distributions of daily precipitation; Bürger and Chen [78] compared regression methods to derive river runoff from large-scale climatic scenarios; Biau et al. [79] used geostatistical methods (kriging) to estimate rainfall; and Coulibaly et al. (2005) [67] investigated the use of temporal neural networks to downscale temperature and precipitation.

Downscaling is not restricted to climatic data and has been used with remote sensing data to derive, for instance, soil moisture maps [80]. Species distribution modeling can also be defined as a general downscaling approach that predicts species distributions from point observations combined with spatially explicit environmental predictors [81]. The term "downscaling" can also be used when creating a land use map from combined input layers at various scales. For example, Remm [82] used case-based predictions to map the distribution of habitat classes from Landsat 7 ETM imagery, grayscale and color orthophotos, an elevation model, a digital base map, and a soil map.

Case-based algorithms are problem-solving methods that learn from experiences at a low level of generalization [83]. They can be considered as an Artificial Intelligence (AI) method that derives results from the data as directly as possible, without the formulation of an intermediate model. Machine learning (ML) specialists distinguish between lazy learning, which typically combines information during the problem-solving phase, and eager learning, which tends to derive a generalization and forget about raw observations after the learning phase [56,83,84]. Remm [82] argued that case-based methods represent a promising alternative for a large range of downscaling problems such as habitat mapping and the prediction of species' potential distributions, especially with large and complex datasets where generalization is difficult.

Based on these considerations, the aim of this paper is to present a lazy learning method, which could be assimilated to a case-based approach, for downscaling LU/LC information for Switzerland from a 100 m lattice of points to a 25 m resolution grid, taking advantage of an existing 1:25,000 digital base map and building an expert system defining possible correspondences between the base map and the land use categories. This method is then applied for three different periods of time to assess land use and land cover change.

2. Materials and Methods

While land use and land cover maps are commonly derived from remote sensing or photointerpretation [85], traditional base maps of Switzerland have been available for more than a century and have been provided in digital format since the year 2000. LU/LC maps derived from the classification of remotely sensed images often have a "salt and pepper" appearance that does not meet end-user demand [26]. Land use derived from aerial photo interpretation can define many different classes of land use/cover categories, but the production is rather time-consuming. National base maps usually lack the thematic details that can be obtained from aerial photointerpretation but generally have an excellent geographic precision to define landscape patches and linear features. Hereafter will be presented the data inputs (Table 1), the downscaling methodology, and the expert system, together with its implementation and validation strategy.

Table 1. Data input sources.

Input	Name	Resolution	Provider	URL
Land Use Statistics (1992/97, 2004/09, 2013/18)	Arealstatistik	100 m	Swiss Federal Statistical Office	www.bfs.admin.ch/bfs/en/home/services/geostat/swiss-federal-statistics-geodata/land-use-cover-suitability.html (accessed on 10 December 2021).
National Base Map (2003, 2008)	Vector 25	25 m	swisstopo	www.swisstopo.admin.ch/en/geodata/maps/smv/smv25.html (accessed on 10 December 2021).
National Base Map (2021)	swissTLM3D	25 m	swisstopo	www.swisstopo.admin.ch/en/geodata/landscape/tlm3d.html (accessed on 10 December 2021).

2.1. Data Inputs

2.1.1. Land Use Statistics

LU/LC data are generated by visual interpretation of aerial photographs taken from a Federal Office of Topography (swisstopo)'s aircraft flying at an altitude of 5000 m and taking photos to regularly cover, over a 6-year period, the entire surface of Switzerland [8]. LU/LC maps are obtained by visually interpreting and assigning a LU/LC category to each point of a regular 100 m lattice laid over the Swiss territory, for a total of more than 4 million points over the country.There are three official classifications: (1) the standard nomenclature NOAS04 (72 basic categories which are a combination of LC and LU, 17 and 27 aggregation classes and 4 main domains); (2) the Land Cover nomenclature NOLC04 (27 basic categories and 6 main domains); and (3) the Land Use nomenclature NOLU04 (46 basic categories, 10 aggregation classes and 4 main domains). Three time periods are currently available (1979/85, 1992/97, 2004/09), and the latest version has just been finalized (2013/18) [7].

Strictly speaking, this dataset is not a LU/LC map, because its categories are assigned to points at the intersection of a 100 m grid rather than indicating the predominant LU/LC within each hectare square (Figure 1). It was developed as land use statistics over relatively large zones rather than as an LU/LC map per se. It tends, however, to be often used as an LU/LCC map in many applications [86] and remains the most exhaustive source of LU/LCC information for Switzerland. Even if this dataset is thematically more precise than the classification commonly used in Europe—the Coordination of Information on the Environment Land Cover (CORINE Land Cover, CLC), which has 44 classes [87]—it suffers from a low spatial and temporal resolution. Indeed, LU/LC units are coarse with a spatial resolution of 1 hectare, and a lot of information is therefore aggregated with a large degree of generalization. Consequently, various landscape features, qualities, particularities, and configurations cannot be correctly represented.

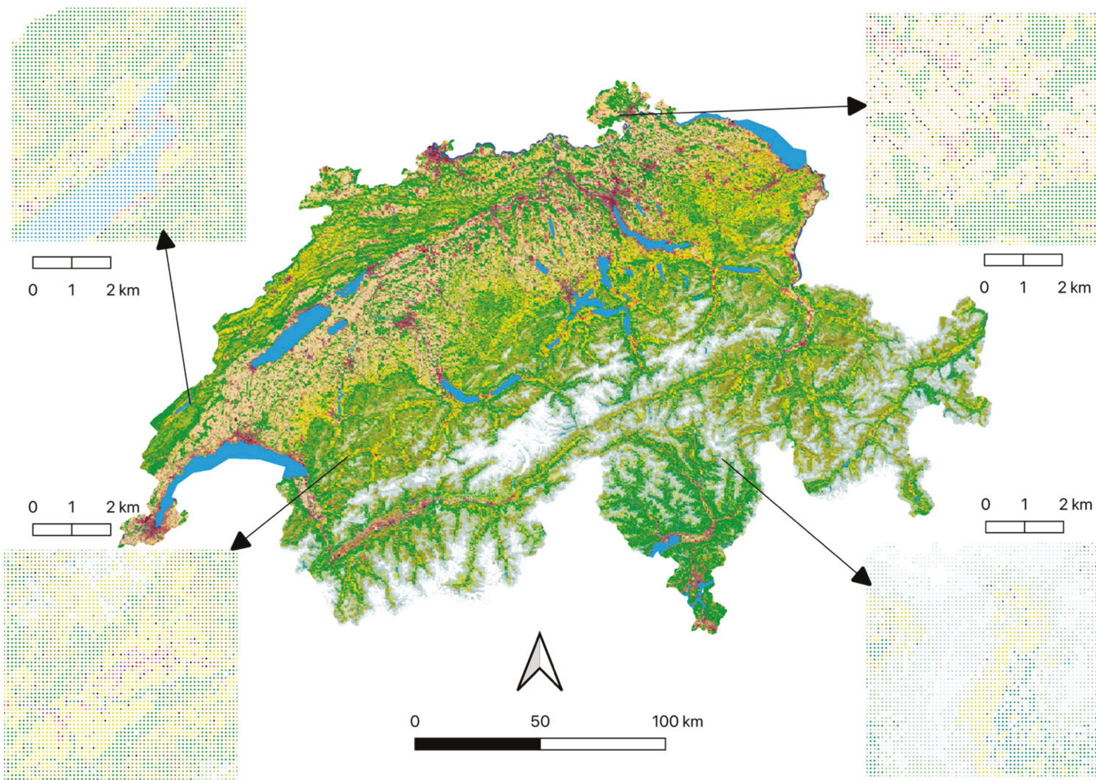

Figure 1. Original LU/LC statistics with 72 classes (Arealstatistik) at a 100 m resolution from the 2013–2018 period.

2.1.2. National Base Map (Land Cover)

The Swiss Federal Office of Topography (swisstopo) provides digital versions of national topographic base maps at a 1:25,000 scale as a landscape model in a vector format. The data model used until 2011 was called Vector 25 and was later replaced by the Swiss Topographic Landscape Model (TLM3D). Both include millions of natural and artificial landscape features, together with their position, shape, type and many other attributes [88]. This land cover information is defined in 29 categories (Figure 2). Data on linear features such as rivers, roads and rails can also be obtained separately. The national base maps (TLM3D) are the geographically most precise source of land cover information for the entire country with a geometric accuracy for different landscape features between 0.2 m and 3 m that is partially updated every year.

2.1.3. Resolution

For the analysis, all available datasets were rasterized either at a 25 m and/or at a 100 m resolution to allow raster overlays. With a surface of 42,000 km^2, Switzerland can be described with approximately 4 million pixels at a 100 m resolution and with 64 million pixels at a 25 m resolution.

2.1.4. Data Quality of Inputs

The two main data inputs of this study are of the highest possible quality from the two main national producers of geospatial data. The first one, land use statistics, has been developed by the Swiss Federal Office of Statistics with state-of-the-art photointerpretation methods, resulting in a very high quality of thematic resolution in the selection of land use classes on each hectare point of the country. The second input, the national base maps, are produced by the Swiss Federal Office of Topography and represent the official geographic representation of the country at a 1:25,000 scale with very high spatial accuracy but a less developed thematic resolution than the first input.

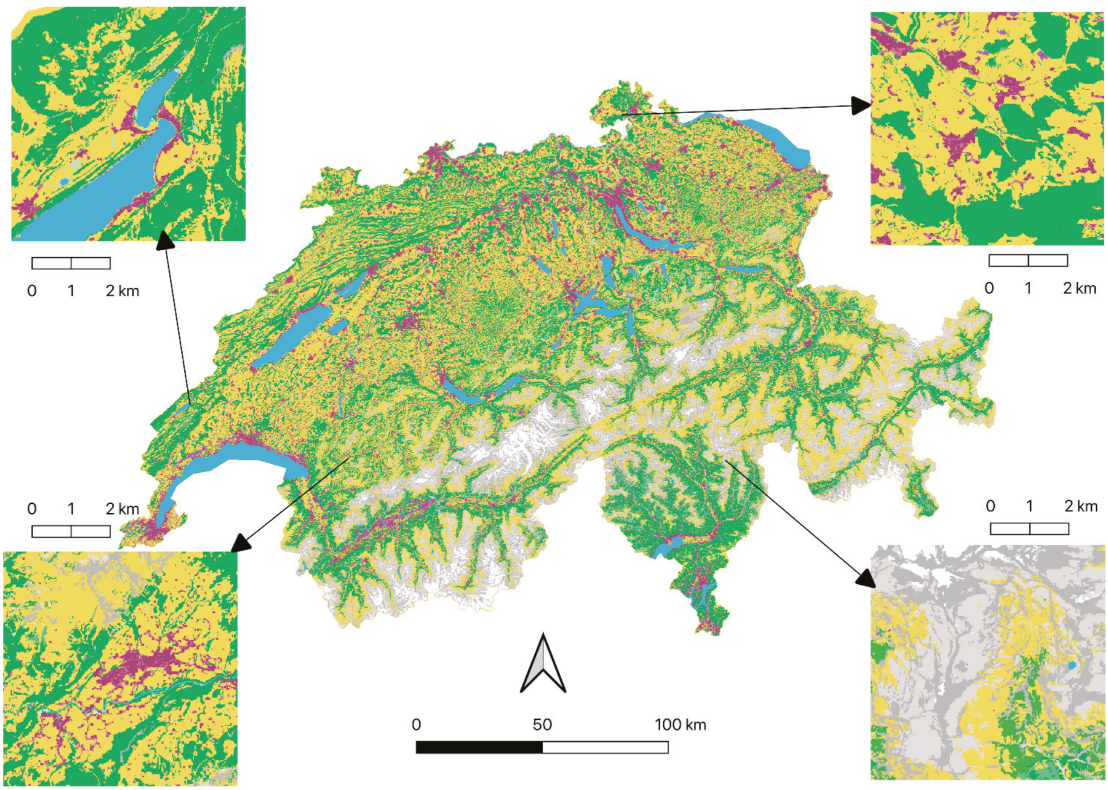

Figure 2. LC information with 29 classes from the National Base Map swissTLM3D for 2021.

2.2. Downscaling Algorithm and Expert System

2.2.1. Downscaling Algorithm

The approach used for downscaling the existing land use information from 100 to 25 m relies on both the geographic precision of the 1:25,000 national topographic base map rasterized at 25 m and the detailed LU/LC categories obtained from the land use statistics available at 100 m. The developed algorithm uses inverse distance weighting combined with an expert system to assign reasonable land use categories at a finer scale (Figure 3).

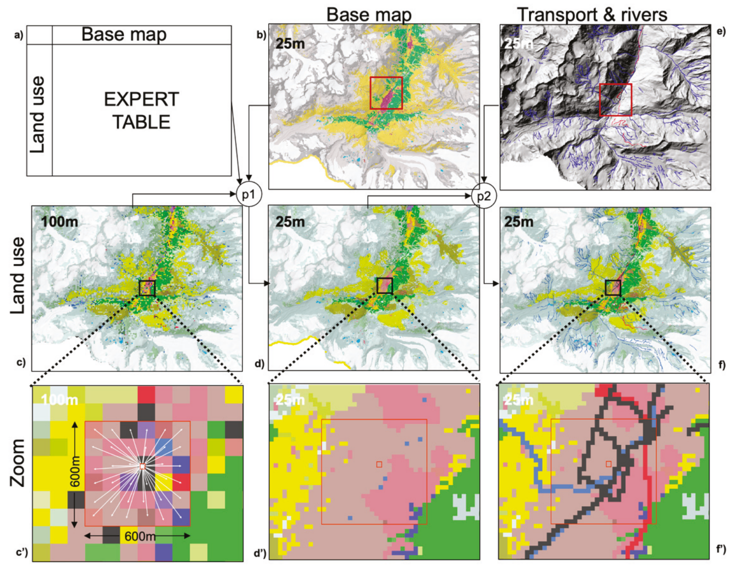

Figure 3. Downscaling land use statistics (2013–2018) in the area of Zermatt from 100 m to 25 m resolution using inverse distance weighting, expert knowledge, national base map, transport and river information at 25 m. (**a**) Expert system (details in Figure 4), (**b**) 1:25,000 base map, (**c**,**c′**) hectare land use information, (**d**,**d′**) downscaled land use, (**e**) 1:25,000 linear features (rivers, roads and rails), (**f**,**f′**) overlay of linear features to downscaled land use at 25 m resolution. Downscaling process (p1) and linear features addition (p2).

	DEFINITIONS	Other type land cover	Forest	Habitation zone	Lake	River	Shrub	Open forest	Marshland in forest	Marshland	Orchard	Gravel pit	Rock	Stone drain in forest	Stone drain	Seedbed	Vignard	Quarry	Clay quarry	Marshland in open forest	Marshland and shrub	Stone drain and srhubs	Track on hard coating	Track on grass	Stone drain in open fores	Glacier	Concrete dam	Stone drain on glacier	Green dam	Building
CODE	**Landuse 100**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
0	Undefined land use																													
1	Industrial buildings																													
2	Land around 1			1																										1
3	One- and two-family houses																													
4	Land around 3			1																										1
5	Terraced houses																													
6	Land around 5			1																										1
7	Blocks of flats																													
8	Land around 7			1																										1
9	Buildings in recreational areas																													
10	Land around 9			1																										1
11	Agricultural building																													
12	Land around 11			1																				1						1
13	Unspecified buildings																													
14	Land around 13			3																										3

Figure 4. Expert system showing the possible authorized Landuse100 categories within BaseMap25 units; (1) represents possible choices, (2) unique choice, and (3) the default choice in case of lack of

decision. Ten land use categories remain unmatched (shaded). Three categories correspond to punctual or linear features (dark grey), and seven categories (light grey) correspond to different types of buildings that were merged with their surroundings (green). A full version of the expert table is available in the Supplementary Material Table S1.

The main steps of the downscaling methodology are the following (data preparation: 1–2–3; process [1] of downscaling: 4–10; process [2] for linear features: 11):

1. Rasterize a land use grid at 100 m resolution from the lattice of points of the land use statistics (Landuse100).
2. Convert to Non-Applicable (NA) land use categories that correspond to linear features (rivers, roads, rails).
3. Rasterize the primary surfaces of the land cover vector base map at a 25 m resolution (BaseMap25).
4. Visit each BaseMap25 pixel (target pixel).
5. Then, according to the expert system table (Figure 4), select the land use categories that could be eligible for the target pixel. In some rare cases, assign the only possible category (then go to point 10).
6. Select among the 36 nearest Landuse100 neighbors those with eligible categories.
7. Calculate the inverse distance to each neighbor.
8. Sum up the inverse distances for each category.
9. Assign to the BaseMap25 pixel the category obtaining the higher score or, in case of lack of decision, assign the best replacement choice according to the expert system table.
10. Repeat steps 4 to 9 for each BaseMap25 pixel.
11. Replace categories wherever river, road, or rail linear features are available from BaseMap25. Only main roads (>3 m wide) and main railways were considered without tunnels and bridges. Underground rivers were ignored. Rivers, railways, roads, and freeways were rasterized at 25 m and added in this order after the first phase of downscaling.

The Inverse Distance Weighting (IDW) calculates a scaled distance to each of the 36 Landuse100 neighbors around the pixel under investigation, and does so in two spatial dimensions (Equation (1)):

$$dj(i) = \mathrm{sqrt}((x25i - x100j)^2 + (y25i - y100j)^2)/maxrange \tag{1}$$

where j spans from 1 to 36 nearest neighbors and i represents each visited pixel at a 25 m resolution and *maxrange* the maximum distance between these pixels.

Then the inverse distances are summed up by land use category (Equation (2)):

$$D_k(i) = \sum_{j=1}^{36} \left(\frac{\lambda_j(k)}{d_j(i) + s} \right) \tag{2}$$

where $\lambda_j(k) = \begin{cases} 1\ if\ landusetype_j = k \\ 0\ otherwise \end{cases}$, and s is smoothing factor.

Finally, the category scoring the highest sum of inverse distances is assigned to the pixel under investigation (Equation (3)):

$$K(i) = greatest_k(D_k(i)) \tag{3}$$

IDW is generally used for interpolating cardinal discrete values (e.g., temperatures, precipitations) but can be also used on nominal values to spatially interpolate missing LC data [89], create super-resolution LC maps [90], or rescale LC data [91]. IDW assumes that values that are close to one another are more similar than those that are at a greater distance. In the proposed method, measured values surrounding the prediction location are considered but then they are spatially weighted (i.e., taking into account the distance of each pixel and the frequency of classes) and constrained (i.e., by the expert system).

Consequently, the proposed downscaling method is filling a geographically very precise map (the base map) with information on the most plausible LU/LC category found in the neighborhood by reducing the possible choices with an expert table. This approach has the advantage of fully respecting the geographical quality of the base map while enriching it with a better thematic resolution.

2.2.2. Expert System

An expert system was used to constrain the possible choices when using information from BaseMap25 to select the most appropriate Landuse100 category (Figure 4). For instance, if a forest patch is defined for a particular site in BaseMap25, the expert system constrains the choice of Landuse100 categories to include only those related to forest. Furthermore, the expert system can also select a default Landuse100 category when the distance-based algorithm fails to make a clear selection because of the lack of eligible land use categories within the searching neighborhood.

2.3. Implementation

Although the algorithm used is relatively simple, it requires extensive calculations on several large grids (25 m resolution grid for Switzerland contains approximately 64 million pixels), which is time-consuming. To ensure the portability of the code on different platforms, the algorithm has been implemented using a set of open-source software and libraries. The programming language is Python 3 [92] using the PyCharm Community Edition (CE) Integrated Development Environment (IDE) [93]. The implemented algorithm relies on the following libraries: (1) the Geospatial Data Abstraction Library (GDAL) [94] to handle raster data; (2) Numpy [95] and math for mathematical operations on large multi-dimensional arrays; and (3) xlrd [96] and pandas [97] for reading and formatting information from Excel files.

To ensure a fast and efficient processing, the algorithm has been parallelized and executed on the High-Performance Computing cluster at University of Geneva [98], allowing to process the entire 64 million pixels grid significantly faster. The analyzed area is subdivided in tiles and the processing of each tile is performed on a different node on the cluster. The surface of Switzerland was divided in 900 tiles (30 × 30), which were associated to 900 jobs in the cluster, using SLURM job arrays. The processing time is on average less than 2 h per tile, but the actual processing time of a single tile is strongly dependent on the user priority and on the cluster load at the execution time. When the results of all the jobs are available, a final script is launched to assemble the 900 processed tiles together in a single image.

The code is freely available on GitHub [99] under an Apache 2.0 license, and a static version can be downloaded from the University of Geneva digital repository [100] under a CC-BY 4.0 license.

2.4. Validation and Accuracy Assessment

The categories of the downscaled LU/LC maps at 25 m (with or without linear features) for the three periods were compared with the categories of the original LU/LC point statistics. A random sample of 500,000 out of 4,129,070 points was used for this assessment. Multi-class classification metrics were used to assess the efficiency of the algorithm to classify each LU/LC category [101–103]. Results are shown as F1-score, which is obtained by harmonic mean from the recall and precision, and Cohen's kappa coefficient [104]. Results were expressed as class F1-scores and weighted means for each dataset, and kappa coefficient for each dataset. Barplots and boxplots are used to display these metrics and the main misclassifications per category. The relative surface area per category was also compared to that of the original Landuse100 dataset [64,105].

3. Results

Results from the land use downscaling are best appreciated at a regional scale (Figures 5 and S1), where the map produced by the algorithm not only preserves the geographic precision of the original BaseMap25 map but also inherits the higher definition of categories (66 categories in the downscaled map compared to 29 categories in BaseMap25). Seventy-two categories were originally found in Landuse100, but a few groupings had to be performed on some less important categories (e.g., buildings and their surroundings). The new map has a much finer grain and can be used for Geographical Information System (GIS) overlays at much finer scales, where the 16-fold increase in the density of pixels gives substantially improved results. Fine-scale details on roads and river networks were also maintained, whereas they are often difficult to represent adequately in coarse resolution raster formats (Figure 6).

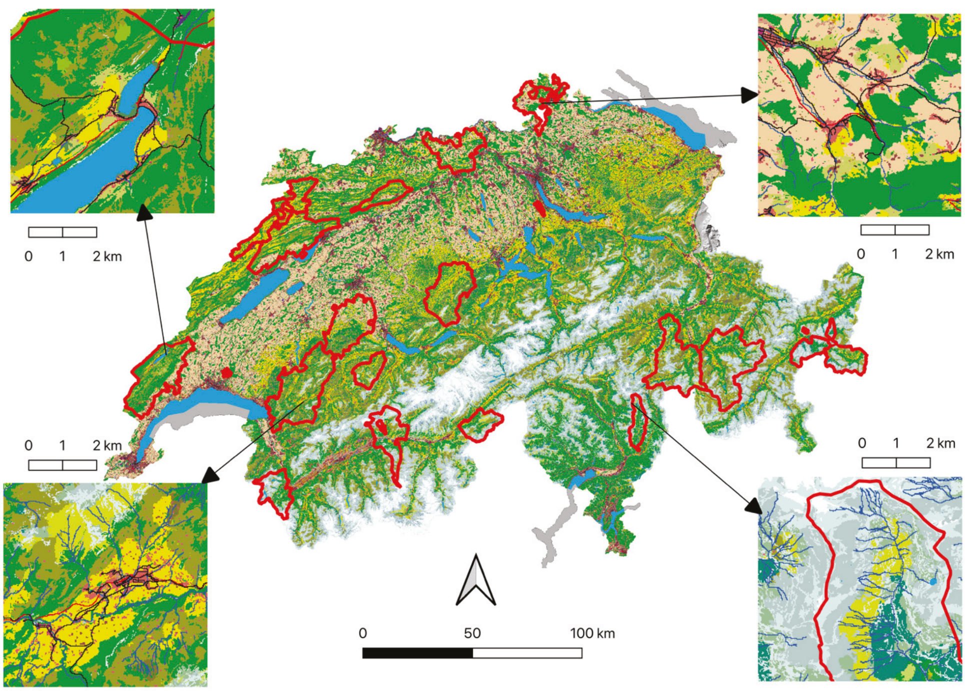

Figure 5. Land use downscaling at 25 m of Switzerland for the 2013–2018 period. Swiss regional parks boundaries in red. (See Figure 6 for legend interpretation.)

The average percentage of similarity for the three periods evaluated between the original points found in the Landuse100 statistics and the resulting Landuse25 classifications is 71% when assessed without roads, rivers, and rails, and 68% when assessed with these linear features. Several categories have a correspondence of 70% or greater. Overall F1-scores and kappa coefficient are high (0.69 and 0.67, respectively). Individual classes F1-scores range from 0.007 to 0.98 depending on the category (Figure 7). Weighted mean F1-scores per dataset range from 0.67 to 0.70. Kappa scores range from 0.65 to 0.69. Categories from the Landuse100 classification that show zero correspondence are those that were not predicted, such as flood protection structures (63), field fruit trees (38), or grooves and hedges (58), and were thus discarded from the validation analysis. The categories that are best respected by the downscaling are those that have a large spatial representation and those that were imposed from the topographic map.

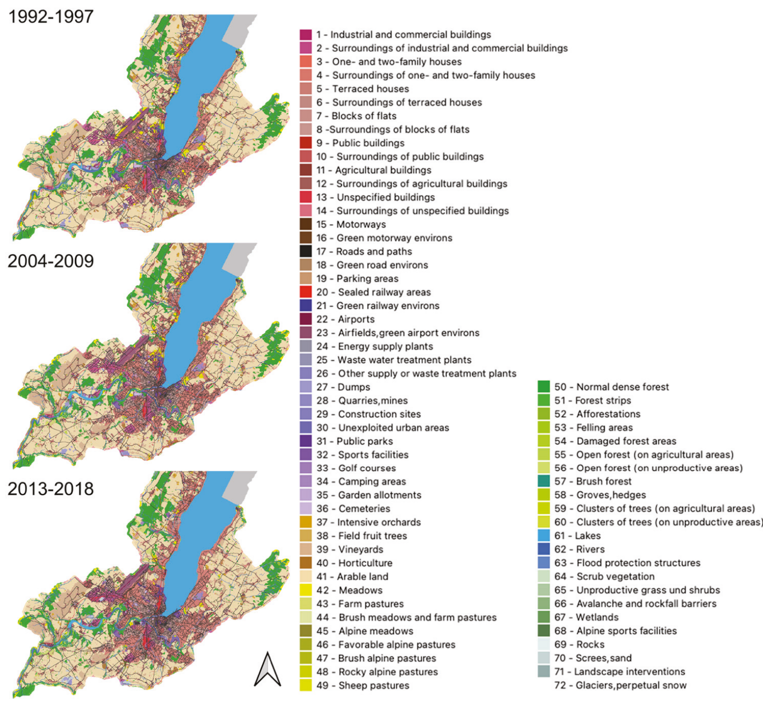

Figure 6. Land use downscaling from 100 m to 25 m and overlay of linear features for state of Geneva for the three periods.

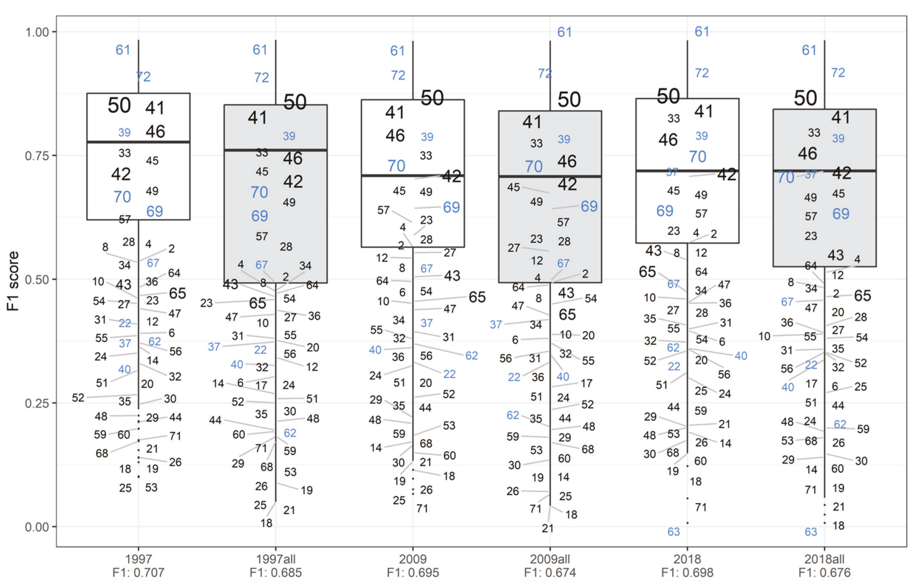

Figure 7. Weighted boxplots showing the F1-scores from the 72 downscaled classes (Landuse25) compared to the original classes (Landuse100), for each period, with ("all") and without linear

features. Numbers along the boxplots represent the land use categories and their size the proportion of each category in the dataset. Blue represents categories attributed based on "swisstopo" original classes; black represents categories attributed based on IDW of the 36 nearest neighbors. Values under each boxplot are overall weighted mean F1-score (F1) and kappa coefficient (k) for the considered year and dataset.

The percentages of misclassification for the downscaling of 2018 without linear features are represented in Figure 8. The major misclassifications concern unproductive grasslands (15%), farm pastures (12%), and meadows (10%). The classes in which the pixels were misattributed are also presented (color in the box). This figure will help in understanding the behavior of the downscaling algorithm to further improve it.

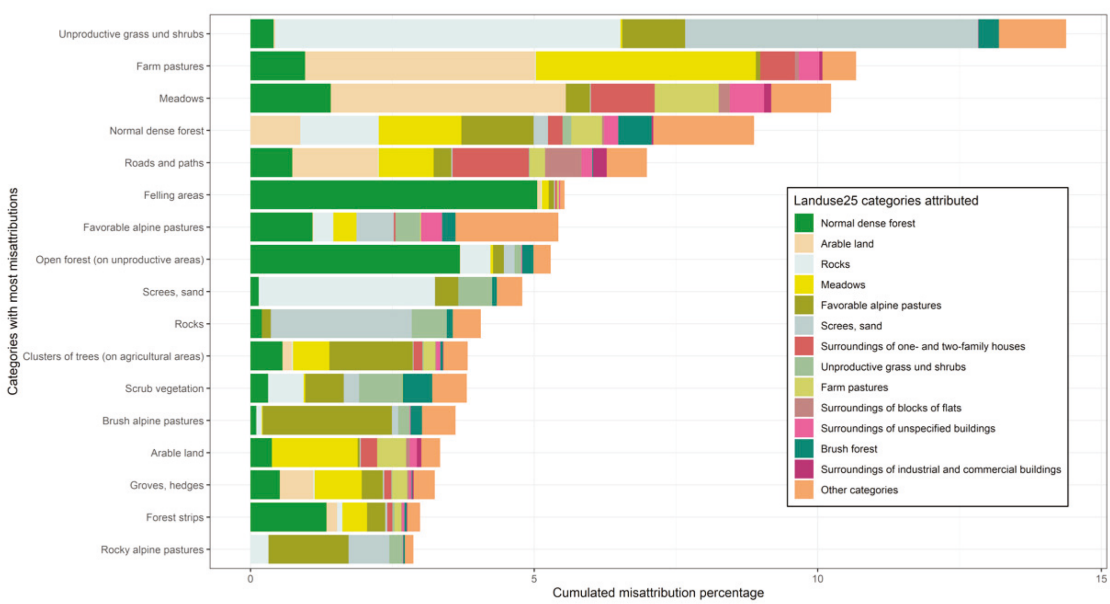

Figure 8. Percentage of all misclassifications for the 17 main classes of the 2018 downscaled LU without linear features. Legend lists categories that were misattributed.

The absolute surface area difference from the downscaled map (Landuse25) categories compared to the original Landuse100 map ranges from −87,585 ha for the category "unproductive grass and shrubs" to +118,174 ha for the category "normal dense forest" (Figure 9). On average, a difference of 532 ha per category is observed. Underlaying reasons for large discrepancies in surface areas (misattributed categories) are further displayed in Figure 8. The relative surface area difference (proportion from downscaled map compared to original) ranges from −100% for small categories that were not included in the algorithm to +355% for cat. 14, "surroundings of unspecified buildings".

Figure 9. Absolute surface area difference from the downscaled map (Landuse25) categories compared to the original Landuse100 map.

4. Discussion

The method presented in this study is a generalizable approach that can be used to downscale different types of geographic information such as results from photo interpretations, classifications of remotely sensed images, or vegetation and soil maps. The general idea is to use the nearest precise point observations to define the attribute of a target pixel at a finer resolution within an area defined by a high-resolution land cover map. Other co-variables such as remote sensing indices (e.g., Normalized Difference Vegetation Index (NDVI)), topographic position, slope, or orientation could also be used to help model the most probable LU/LC category and could certainly further improve the present method.

In the case study presented here, the use of a national topographic base map at a 1:25,000 scale to define main land cover patches guarantees a perfect overlay with official maps. Indeed, topographic base maps are now available in digital format and are widely used as reference maps in most studies and field work. The possibility of matching the geometry defined by base maps with detailed land use categories reinforces the chance of uptake from end-users. However, some recent changes in LU/LC that might be visible from remote sensing images could be lost if involving changes between incompatible land use categories as defined by the expert system.

One of the main strengths of the proposed approach is that it avoids the "salt and pepper" effect generally resulting from the classification of remotely sensed images [26], except in the case of object-oriented classifications [106]. We believe that our approach could be particularly useful in this respect and could be used to smooth out land use maps obtained from remote sensing classifications. In such a case, land use statistics would be replaced by the land use classification obtained from supervised or unsupervised classification of the remotely sensed image, whereas the land cover information would still be retrieved from the national base map. Moreover, with the increased spatial resolution and the removal of the "salt and pepper" effect, LU/LC changes are more evident and can be assessed more easily (Figure 10).

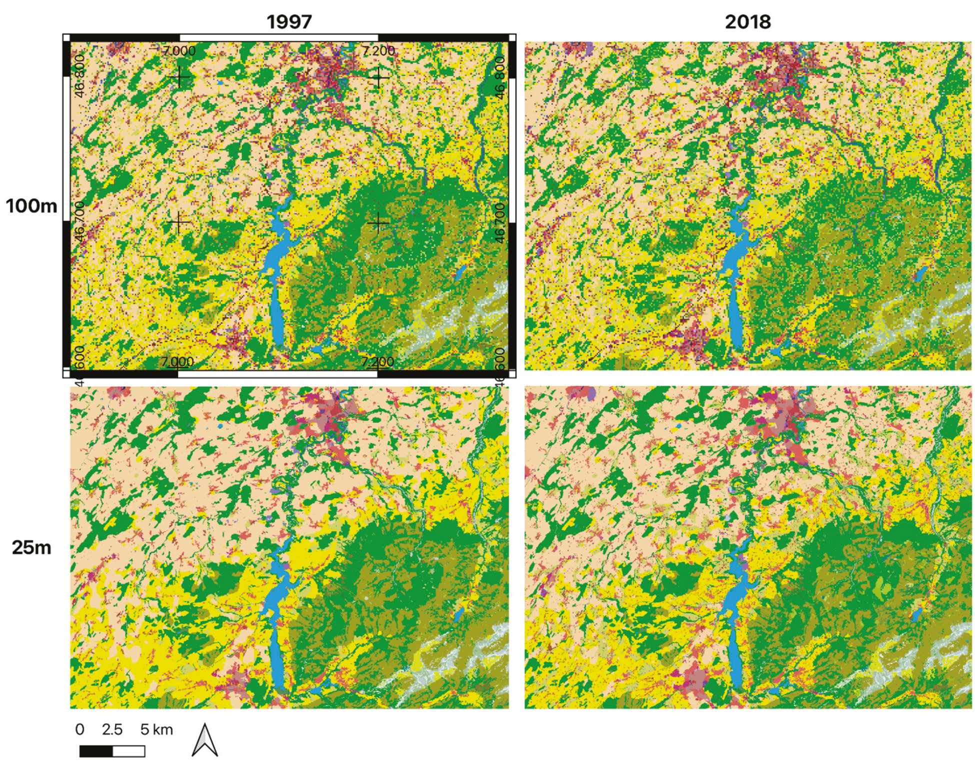

Figure 10. Comparison of the 1997 and 2018 LU/LC data with original 100 m resolution (**above**) and the downscaled outputs at 25 m (**below**) for the Bulle and Freiburg cities. Urban expansion (as well as other land cover changes and the smoothing effect) of this economically active region can be more easily visualized with the improved spatial resolution.

The proportion (71%) of exact matches between the land use categories recorded at the 100 m resolution lattice points of the Landuse100 statistics and the corresponding points in the downscaled map (25 m resolution) is particularly encouraging. Discrepancies appear to result mainly from the change in scale and geometric precision brought in by the 1:25,000 base maps. The fundamental difference in approach between the land use statistics (punctual) and the topographic map (surface) is also important. A visual check confirms that most divergences mainly occur along boundaries of patches of different land use and along linear and small features. By using an inverse distance calculation—which gives a higher weight to close-by information—to choose the best land use category for each pixel, we greatly favored the retaining of input land use categories at an observed location in the result. This effect can be modulated by the smoothing factor in Equation (2).

The approach could be used at even finer scales by rasterizing for instance the topographic maps at 10 m instead of 25 m or using a regional map at a finer scale (1:10,000). Getting accurate land use information is crucial for calculating landscape indices such as those obtained from FRAGSTAT [107]. As demonstrated by Uuemaa et al. [108], changing grain size can have a significant effect on many landscape metrics. Therefore, one should pay attention to the scale at which a given landscape metric is calculated, and what grain size of land use maps is best adapted for the purpose, as there is no single land use scale which is "best" for observing and managing changes in land use patterns.

The implementation of a case-based reasoning algorithm in Python code proved to be a very efficient approach given the very large number of pixels (64 million) to handle but required the development of a purpose-written software. The availability of tools for implementing case-based approaches within existing GIS packages would certainly be very useful for many applications. One such tool has been developed by Remm [82] using Microsoft Visual Studio.NET, and this can predict several response types (binomial, multinomial, continuous, and complex) based on continuous and categorical predictors.

Riitters [109] mentions the practical trade-off that exists between the generality, precision, and realism of a method, as previously proposed by Levins [110], and emphasizes that generality and realism should be maximized at national scales, while precision should be optimized at local scales. Indeed, the use of the same raw data to develop models at different scales will enhance thematic and geographic comparisons between disciplines and across scales. Methods to upscale and downscale data are therefore central to local, national, and global environmental assessments.

The presented approach contributes to tackle the need of increased spatial resolution of LU/LCC information. However, the temporal issue remains a major problem. Indeed, land cover changes are caused by either natural or anthropogenic sources such as climate change, demographic growth, and economic growth [111,112]. Therefore, the state of land cover is highly dynamic and involves an inherent challenge for its mapping and monitoring that remains not adequately addressed [85]. Timely and reliable information on land cover change is crucial to efficiently mitigate the negative impact of environmental changes [113,114]. Traditional environmental data collection (e.g., field data collection) suffers from many shortcomings, among them the data inconsistency caused by changes in reporting methodologies through time, the gaps (missing measurements) in data series, and the fact that it is notoriously time-consuming and labor-intensive [115]. One of the main advantages of remotely sensed data collection is that it can provide a synoptic and repetitive view of a given area/region. With the opening of different Earth Observations (EO) data archives such as Landsat [112,116,117], it becomes possible to build consistent time series (i.e., image of the same location at regular intervals) to compare different periods of time and derive trends [118–120].

At the national scale, various attempts have been made to use satellite imagery, but unfortunately, no processes are currently in place to routinely generate accurate, consistent, and regular LU/LCC data. These large volumes of freely and openly available EO data are still underutilized and are not effectively used for national environmental monitoring. Therefore, mapping and monitoring LU/LC changes remain as challenges that are not adequately addressed at the national scale, and new methodologies are required to produce consistent and reliable yearly, medium-to-high-resolution (spatial, temporal, thematic) time series of LU/LCC data and projections of their (future) change across Switzerland to inform national and regional environmental policies and planning.

With the opening of different medium-to-high-resolution satellite EO data archives such as Landsat or Copernicus and the development of advanced data science techniques (e.g., Big Data, Artificial Intelligence, High-Performance Computing), it now becomes possible to build consistent time series of LC, to investigate the spatio-temporal dynamics of LC, and to perform quantitative assessments of LC dynamics, by comparing different periods of time, deriving trends, and determining environmental trajectories [121]. This can generate a consistent and reliable LU/LC time series that will help to understand the evolution of LU/LCC in Switzerland over the last 30 years and to model future changes according to plausible scenarios by 2050 [122,123].

To reach this objective, an essential pre-condition to support user applications and generate usable information products is to facilitate data access, preparation, and analysis. The systematic and regular provision of Analysis-Ready Data (ARD) can significantly reduce the burden of EO data usage. To be considered as ARD, data should be processed according to a minimum set of requirements (e.g., radiometric and geometric calibration; atmospheric correction; metadata description) and organized in a way that allows immediate analysis without additional effort [124,125]. In Switzerland, more than 37 years of satellite EO Analysis-Ready Data over Switzerland are made available by the Swiss Data Cube [126,127]. The increasing availability of EO data together with the improved computing and storage capacities allow monitoring, mapping, and assessing LU/LC and its change over time on large areas in a consistent and reliable manner. This favors the development of annual, high-quality LU/LC products based on time series data and can inform on class stability and transitions [128].

5. Conclusions

The proposed downscaling approach allowed for combining the geographic precision of existing topographic base maps with the thematic details of photo-interpreted land use statistics. Improved land use maps open the door to more accurate watershed analyses, species and habitat distribution modeling, and species dynamic models of migration. Accurate land use information is also the base for developing sustainable development indicators defining the structural and functional attributes of landscapes.

The proposed approach could be implemented for three time periods. It allowed for an efficiently downscaled LU/LC at a spatial resolution that is more suitable for environmental change monitoring. The increased spatial resolution removed the "salt and pepper" effect, and consequently, LU/LC changes are more evident. However, the changing definition of the base map input across the years resulted in discrepancies in the resulting downscaled maps that are refraining their use for land use change analyses. We therefore recommend using the original land use statistics data for trend analyses and our downscaled data for GIS analyses at each time period. The presented approach contributes to tackling the need for increased spatial resolution of LU/LC information, but the temporal issue is still a major problem. The use of dense time series of satellite data such as those provided in the Swiss Data Cube can be a promising solution to investigate to obtain high spatial and temporal LU/LC data over the country.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land11050615/s1. Figure S1. Final result of the downscaled Land Use/Land Cover at 25 m for the period 2013/18. Table S1. Full version of the expert table.

Author Contributions: Conceptualization, A.L. and R.M.; methodology, A.L.; software, A.L., G.G. and D.R.; validation, A.L. and N.K.; formal analysis, A.L., G.G. and D.R.; data curation, A.L. and N.K.; writing—original draft preparation, G.G., A.L. and R.M.; writing—review and editing, all; visualization, A.L. and N.K.; supervision, A.L.; project administration, A.L.; funding acquisition, A.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The results presented in this study are openly available in Yareta, the University of Geneva Digital Repository, at: https://doi.org/10.26037/yareta:dlx3hu54jfa3ne3c2xjfcnqpxm (accessed on 21 February 2022) and in the ValPar project Spatial Data Infrastructure at: http://valpar.unige.ch:8080/geonetwork/srv/eng/catalog.search#/metadata/da78fa9f-a756-4538-a28a-8be7d53d4676 (accessed on 21 February 2022). The source code of the algorithm is available at: https://github.com/ggiuliani/LULCdown (accessed on 21 February 2022). Publicly available datasets were analyzed in this study. These data can be found here: Land Use Statistics (https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/erhebungen/area.html, accessed on 21 February 2022); Base Maps (SwissTLM3D—https://www.swisstopo.admin.ch/en/geodata/landscape/tlm3d.html, accessed on 21 February 2022).

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Conflicts of Interest: The authors declare no conflict of interest.

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Article

Strategic Directions: Evaluation of Village Development Strategies in the Case of Applicants for the Hungarian Village Renewal Award

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Abstract: Village roles have changed significantly in Central Europe over the last century and a half. In our article, we mainly deal with the conditions in Hungary. Based on the relevant literature, we follow the changing role, problems and presence of Hungarian villages. Our research focuses on evaluating village development strategies; thus, an essential part of the article is the presentation of the European and Hungarian village renewal movement, as the 50 settlements examined are also part of the settlements launched at the Hungarian Village Renewal Award competition. In this research, the 50 settlements were divided into three groups according to their role in the settlement network. The settlement group analysed their development priorities by summarizing the Hungarian Village Renewal Award applications. As a result, it was found that the development directions of the villages belonging to the individual settlement groups can be well separated from each other. The choice of the settlement development strategy is greatly influenced by the distance from the central settlements and the settlement network situation. We compared our results with the analysis of the strategies of some foreign villages (located in the former socialist bloc) and then examined the Hungarian village surveys of the last century and a half, focusing on land use changes and their role in development. As a result of the analysis, it became clear that the importance of land use in the life of villages in the initial period decreased spectacularly over time and was replaced by employment and the role of the settlement network. The main result of our research is that we have proven that the strategic priorities of village development can be grouped based on the position of the villages in the settlement network, and the priorities are mainly determined by the size of the central settlement and the distance from it.

Keywords: village; strategy; development priorities; land use

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1. Introduction

In the last century, the situation and role of villages have undergone a significant transformation, both in the western part of Europe and in the former post-socialist area. Villages have taken on a new role, looking for the correct answers to the challenges of the 21st century. Accordingly, a new type of development measure is needed among small settlements.

In our article, we aim to analyse the villages' strategic development priorities and present and interpret the renewal and development plans of the increasingly tricky small settlements and their specific development elements. Knowledge of these elements can help both professionals and decision makers to develop proposals for development programs at higher territorial levels. In our article, we are now looking for the answer to the question of which development elements and priorities determine the strategy of each village and to what extent the situation of their settlement network influences this. This article focuses on the analysis of Hungarian villages. As a result, we draw general conclusions from their results.

To gain an accurate understanding of the situation, we considered it necessary to present the history of the villages to the present day, including the changed circumstances, which may explain some development decisions, even seemingly irrational. Our studies also paid particular attention to the resources on which the villages base their development. To this end, we looked at the factors based on how the surveys of the last 150 years grouped the villages and which development factors were emphasized for each type of village. We did this because, in our view, arable land as a local resource can be an essential element in the strategic development of small settlements.

However, our primary goal is to analyse the village development strategies by examining the applications of the villages that participated in the Hungarian Village Renewal Award. Therefore, it is essential to present the details of the Hungarian (and European) village renewal movement and the related Village Renewal Award. Without this knowledge, the reader may be confused by the grouping system of our results.

The structure of the article and the logical connection of each Section are shown in Figure 1.

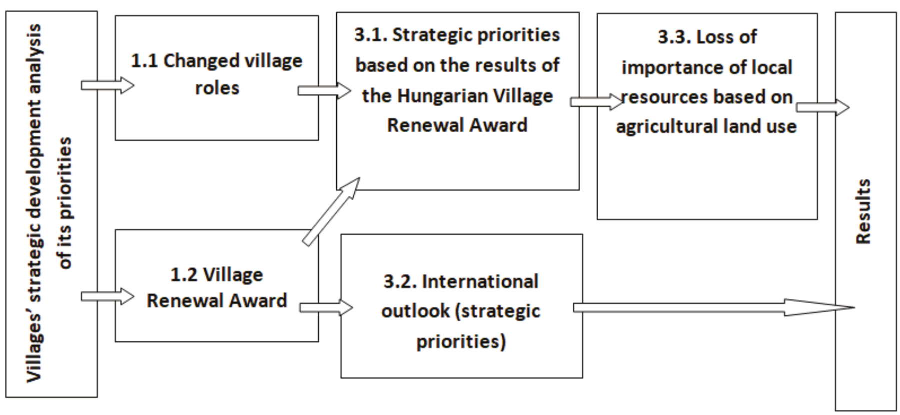

Figure 1. The logical connection of the researched topics.

1.1. Changed Village Roles

As a result of socio-economic changes in the last century, the settlement network in Central Europe has changed significantly; thus, the traditional role of villages has also changed. The villages of the countries of the socialist bloc underwent changes that changed from country to country after the change of regime. However, the geographical location of the settlement (deprived area or urbanisation) and the land ownership structure played a decisive role in the changes. Development opportunities are determined by political heritage, but also by the weakening of the role of agriculture in the economy [1], urbanisation [2,3], the backwardness or rapid development of certain areas [4], and sustainability in agriculture [5–7], which define research directions. In addition, the European Union's agricultural [8,9] and rural development [10] directives, which already include complex development aspects [11], set out development opportunities. Research in different fields of science also shows that supporting different local initiatives can significantly contribute to rural development [12,13].

Despite the similar political system, different trends can be identified in each country during the changes in the settlement network [14]; thus, we briefly present the changes in the settlement structure in Hungary since the 19th century, as this is essential for analysing and understanding the current situation. Furthermore, we want to present the changed situation through the processes in Hungary, where given that Hungary was located on the eastern side of the Iron Curtain, the process created more extreme situations than the European average.

Hungary was traditionally characterized by agricultural production in the 19th century. A system of large feudal estates characterized the century, and this estate structure was and survived until the middle of the 19th century.

Before the First World War, the vast majority of the Hungarian rural population lived off agriculture [15], under challenging conditions, two of which were due to the underdevelopment of the large estate system and industry. This situation did not improve between the two world wars [16]. According to contemporary interpretations, the village was the scene of traditional peasant society and agricultural production. However, it was gradually transformed into a new, more diverse form of settlement [17]. However, the "village = agricultural settlement" formula, due to socialist economic and settlement policies, became invalid even before the change of regime [18,19]. Rural society was no longer composed exclusively of the agricultural population [20], and after the change of regime, the process intensified further.

Due to the communist takeover after the Second World War, the self-determination of local governments ceased to exist, several settlements came under the joint control of the council, and collectivizing agricultural policy and intense industrialisation exacerbated territorial differences [21]. The general phenomena of the first stage of socialism are industrialisation at a stormy pace, the reorganization of agriculture, the liquidation of homesteads (and the creation of new homesteads), the stratification of employment, and the rapid, accelerating growth of cities. As a result, the change in the state of the villages became the most characteristic. There were no mature types of transforming village at that time. Their general feature was only the separation of the traditional unity of settlement, agriculture and peasantry [22].

In socialism, the most crucial sector of the economy was industry, and in 1970, 10–15% of the village population was industrial and one-third mixed [18]. The transformation of villages was also significantly influenced by the effects of settlement and social policy: the construction of the socialist economy (collectivisation, industrialisation) favoured certain areas, and according to the principles of settlement network planning, the differences in supply increased; thus, the less-favoured areas due to the structural network and the poor condition of the housing stock are becoming increasingly disconnected [19]. By the end of socialism, however, due to the unified treatment of socialism, the villages were increasingly losing their former character [23].

Following the change of regime, the 1990 Local Government Act gave settlements an entirely new legal status, the municipalities were "freed" from the subordination of the territorial level, the principle of self-government considered the possibility of self-government as a fundamental part of the democratic system [24,25], and municipalities, regardless of size, were granted complete municipal independence.

As a result of self-sufficiency, local governments have made significant economic and infrastructure development progress. However, the value of improvements is diminished because most municipalities have only achieved partial results without a comprehensive renewal strategy and have stalled since initial improvements [26]. The great euphoria of independence was thus soon followed by rapid sobriety [27]. However, in the first half of the 1990s, there were signs of insolvency in some elements of the fragmented structure, especially in small villages with structural problems [25].

The framework of the development of the settlement network has changed radically. The separation of individual villages and the formation of new villages have been facilitated [28], the population of tiny villages has become more fragmented, the number of dwarf villages has increased [29,30], the number of local governments has increased to over 3000 and the competition of settlements has intensified. "Villages have entered the free market of their settlements", in which their relative position is determined by their geographical location, their endowments and the local policies that exploit them [19,31]. Thus, the introduction of free local government and normative financing fundamentally changed the previous structure. As the local government was associated with rights and obligations, there was a great deal of tension between local governments between the elements of a fragmented system and the allocation of resources [25].

Following the regime change, the social processes caused by the sudden freedom also rearranged the roles in the settlement network [32]. The development and population-absorbing power of the cities had severe consequences for the villages outside the agglomerations of the big cities: the small settlements had to face the worsening processes of emigration and ageing: primary care was lost as well as services for the local society, society was ageing and services had deteriorated further [20,33]. Patrick Drudy called this process the "cumulative cycle process" [34]. Thus, the prevention of unfavourable demographic processes and the strengthening of local society became the primary goals of the survival and development of villages.

The most characteristic features of the transformation of the settlement network were geographical deconcentration and territorial differentiation, which resulted in regional transformations. Several rural areas rose in parallel with the classical suburbanisation processes [35,36].

As a result of the settlement network and the urbanisation of society, the emigration of young people to cities has intensified. The population of rural villages has decreased, and society has become older [37]. However, in addition to the changing role of villages, the social demands placed on them have also changed. The "urbanisation" of the villages, the supply expansion and the improvement of the quality of locally available services became basic expectations. At the same time, in the age of digitalisation, the village can also be seen as the opposite of the accelerated urban way of life: the calm living environment and the need for a "rural" way of life are becoming more and more critical [38]. The above two opposite processes also set the villages on a new development path. Due to the changing roles and expectations, the new development directions and strategies could be the breaking points of the villages, through which the individual small settlements could become successful.

Villages need to place more and more emphasis on their development as a result of urban competition such that they can be an attractive alternative to the city for the population. To this end, (conscious) settlement development has become essential for the villages. Their renewal and development can be seen as a potential living space by the locals and the people wishing to settle here. The decline and then renewal of villages (and rural areas), the conscious development of settlements, and, over time, the growing number of leading-edge villages have given rise to a village renewal movement that maintains villages (and rural areas). Aimed to preserve them, increase their vitality, and develop them sustainably [39]. Along with these principles, the Hungarian and European Village Renewal Awards are organized every two years, described in detail in Section 1.2.

1.2. Village Renewal Award

From the end of the 20th century, the renewal of villages and rural areas, village and rural development has become more and more critical [40], the principles of which were enshrined in the 1996 Cork Declaration [41], and which were further developed in 2016 [42]. The implementation of the Cork Declaration is being developed by the European Union's Directorate—General for Agriculture and Rural Development within the framework of the Common Agricultural Policy [43]. Today, village renewal has also become a domestic and European movement. As a result, dozens of villages can be set as an example in front of other small settlements. In our research, we deal with these villages: we want to present the development of those villages which, recognizing their changing roles, were able to provide an appropriate response to the challenges of the new millennium and serve as a positive example for other settlements.

Our research examined the results of the settlements that participated in the Hungarian Village Renewal Award competition. The Hungarian Village Renewal Award competition grew out of the village renewal movement launched by the European-based European Rural Development and Village Renewal Working Community (Europäische ARGE Landentwicklung und Dorferneuerung) [44,45]. The European Economic and Social Committee has also prioritised this issue, as exemplary initiatives, good practice and the dissemination of good practice are essential for the regeneration of Europe's rural areas [46], and the Village Renewal Movement seeks to motivate villages in [47].

The European Community organizes the European Village Renewal Award for Rural Development and Village Renewal. (The Working Community operates voluntarily as an international NGO, independent of EU institutions and bodies.) The European Village Renewal Award has been announced since 1990, with an international panel of experts giving an opinion every two years on the success of each applicant's work [39].

The application initially focused on two strategic themes: the situation of villages (landscape, settlement, cultural heritage and infrastructural characteristics) and related developments (cultural landscape, agriculture, building stock, renewable energy, local quality of life, or social and cultural institutions). In 1998, the call for proposals was modified. First, the development goals were divided into ten, later seven and eight, and since 2012, nine topics. These were the most important strategic areas of village development, and applicants had to present their development results in these areas [48].

In addition to presenting thematic developments, comprehensive conceptual planning and strategic processes, sustainable development and partnership have become increasingly important in the call for proposals, focusing on individual initiatives, dialogue between politicians, experts, public authorities, local people and regional cooperation.

Each European Village Renewal Award competition has its motto, and compliance with it is a priority during the competition. The competition's motto has constantly been changing over the last 30 years. It is clear from each title that the challenges the advertisers were looking for have definitive answers in the current period (Appendix A). (Of particular interest is the 2020 motto that local responses to global challenges are the biggest challenge).

The villages participating in the European Village Renewal Award are evaluated according to a complex system of criteria, taking into account the initial situation, development goals and processes, and the individual development projects in each thematic area.

The Hungarian competition is also closely related to the international village renewal competition. In general, we can discuss the embedding of the Hungarian competition in the European Village Renewal Award competition, considering that after the Hungarian competition, the winner will represent Hungary in the European competition. The Hungarian Village Renewal Award competition is announced every two years. The applicant settlements document the life course and development goals of the villages for the development period, as well as the programs and measures taken for these purposes. The most important aspect is how complex the programs implemented during the development serve the development of the village, and whether they provide an appropriate answer to the challenges and problems raised by (the village). The thematic programs examined during the development are the following:

- Strengthening environmentally friendly agriculture and forestry;
- Responsible and environmentally friendly resource management, use of renewable raw materials;
- Maintaining local supply and employment opportunities and creating new ones;
- Renovation of the old building stock worth preserving, construction of new, high-quality buildings;
- Modern social institutions, creation of opportunities for socio-cultural life;
- Strengthening the identity and self-awareness of the local population;
- Developing the skills and motivations of the population to develop their commitment to the community;
- Promoting economic, social and cultural equality for all ages, nationalities and minorities;
- Networks, inter-municipal relations.

The grouping of the programs into thematic areas as required above requires a tight strategic approach when compiling the application documents (and during the decision-making process). In addition, it makes it easier to compare individual villages.

2. Materials and Methods

In the course of our research, we worked with the data of 50 villages launched in the Hungarian Village Renewal Award competition (Figure 2). The 20–40-page application materials of each village contain statistical data according to the Hungarian Central Statistical Office (KSH), local characteristics (e.g., several local associations, NGOs and number of members) as well as development goals and implemented improvements. The application materials show the aggregation and systematization of data that also contain the national register (KSH) data; thus, their separate collection [49] has not become necessary.

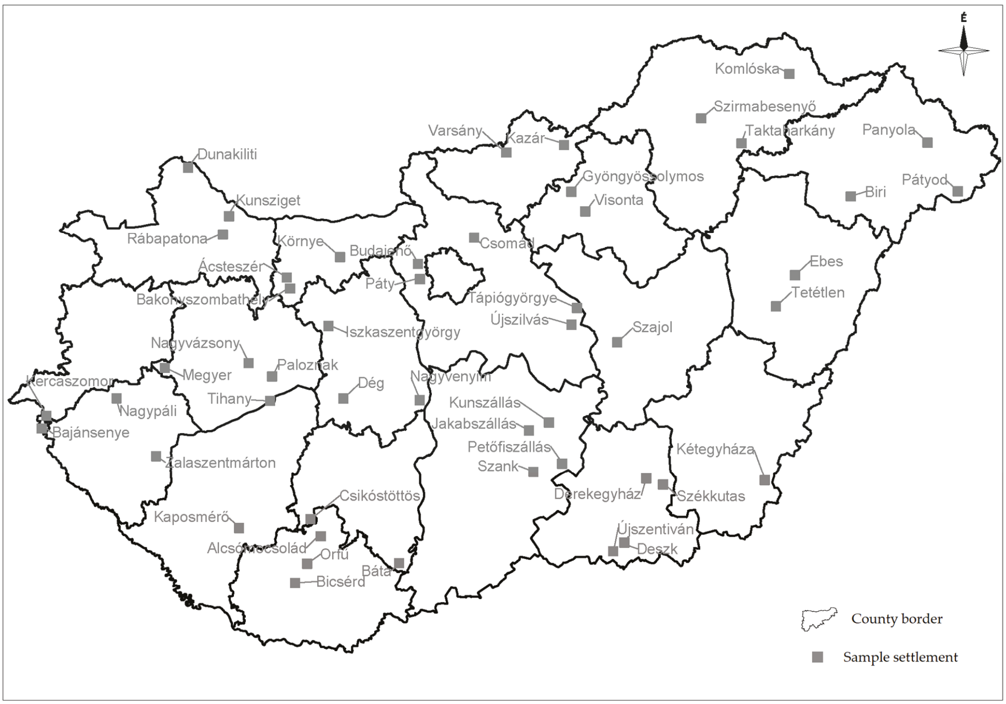

Figure 2. Location of sample settlements.

According to the literature data, the 50 villages represented a diverse set of settlements that could represent the Hungarian village types. Therefore, for the analysis, the sample settlements needed to have different villages in terms of geographical location, settlement size and the settlement network's role.

One of the hypotheses of our research is that the nature of the development strategy, the selection of the development directions and the essential characteristics of the strategy are determined by the regional location of the villages and their role in the settlement network. Accordingly, we classified the sample settlements into three categories: settlements located in metropolitan agglomerations (in the vicinity of county capitals), settlements located in small-town catchment areas, and settlements located in depopulated areas; the latter category included all the settlements in the catchment area of small towns with less than 10,000 inhabitants. Grouping was performed according to the central settlement of each settlement group, differentiated according to the function (and size) of the central settlement. Thus, the basis of the grouping was not the villages but the cities that represent the spatial organizing power of the villages. (The grouping principle was also supported by the results of the settlement network research carried out by VÁTI (Urban Planning Office, later VÁTI Hungarian Regional Development and Urban Planning Nonprofit Ltd., Budapest, Hungary) in the 2000s, according to which small towns and new settlements in terms of their function are in many cases unable to perform the task of a regional organization. Thus, the availability of actual centres from smaller settlements in the vicinity of these "appearance" cities becomes problematic, and the quality of life in villages located in functionally deprived areas decreases [31].

In our research, the classification of settlements into three groups was validated using KSH basic data (KSH serial number, "success index" and pattern analysis of basic statistics of sample villages and their neighbours-mean, standard deviation, median, minimum, maximum, confidence interval) [50]. Thus, the individual examinations were performed separately for the groups. After the classification into three groups, 17 of the examined settlements belong to metropolitan agglomerations, 20 to small-town catchment areas, while 13 are located in areas without urban areas (Figure 3).

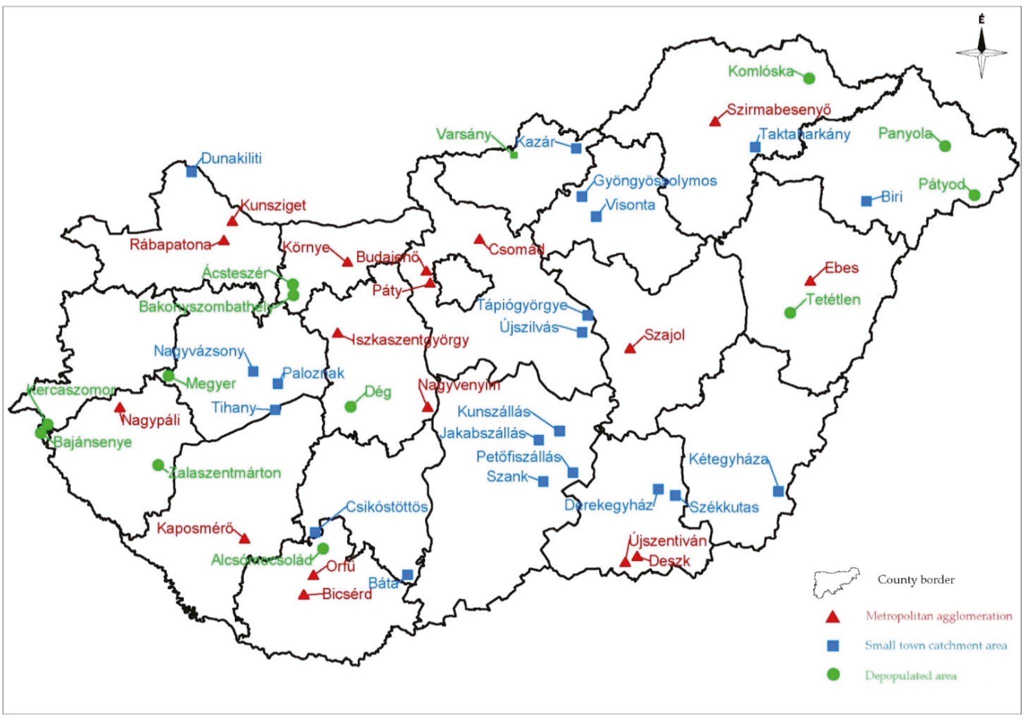

Figure 3. Location of sample settlements by groups of settlements.

An overview of the 50 entries in the Hungarian Village Renewal Award competition was necessary to analyse development strategies. (During the analysis, the results of the settlement groups were evaluated in general and separately according to the evaluation criteria.) The analysis of the tender participants in 2005–2019 used its tender documents and evaluation results. Based on these, the intervention's justification, effectiveness and quality had to be assessed for all thematic areas; they could be rated as poor, average or exemplary. The evaluation was performed with a value on a scale of 0–10 points per subject area. (The panel of experts has been scoring the applications since the 2017 competition, before which the grading was based on an oral evaluation by the committee members. Applications before 2017 in the absence of a score were evaluated based on written application materials and personal experience).

According to the critiques, the interventions of each village by thematic area were considered successful if they were exemplary in all respects—justification, effectiveness, quality—and the development strategy was successful if exemplary interventions were implemented in all thematic areas.

Following the analysis of village renewal strategies, we analysed the village surveys in Hungary (at the national level), with a particular focus on land use. In the analysis, the methods of five nationwide surveys, which faithfully reflect the settlement population of the given period, were listed, emphasizing the methodological changes of the individual surveys and the modification of the cluster-forming variables of the settlement groups defined by the surveys.

3. Results

3.1. Strategic Priorities Based on the Results of the Hungarian Village Renewal Award

Our research focused on which areas the villages had hoped to develop in recent decades, which areas they had focused on, and what thematic programs they had set to develop the village.

The detailed analysis covered the applications of the 50 settlements that participated in the Hungarian Village Renewal Award competition, which were examined primarily based on their role in the settlement network and the emphasis of their development strategy.

The exact names of the thematic programs are presented in Section 1.2, and for the sake of simplicity and transparency, these programs will be referred to as follows:

- Agriculture and forestry;
- Sustainable resource use;
- Employment;
- Quality building stock;
- Socio-cultural life;
- Local identity;
- Community building;
- Equal opportunities;
- Network connections.

Examining the applications of the 50 villages, it became clear that the settlements carried out improvements following several priorities. However, the question arose as to whether there is a common feature between the different development programs and strategies or if the presented villages are independent examples of successful developments.

As the characteristics of the development strategies and the emphasis on the individual thematic areas within the strategy are greatly influenced by the role of the village in the settlement network, the results of the villages were examined into three settlement groups presented in Section 2.

The analysis of the development strategies of the settlements for the nine thematic areas of the Village Renewal Award competition presented above confirmed the assumption that the role played in the settlement network significantly influences the choice of the development strategy. The standard features of the strategies separated according to the settlement groups have shown that, depending on the role played in the settlement network, some topic areas are given more emphasis, and others become completely insignificant and unjustified.

The results of the 50 sample settlements and the emphasis programs of the development strategies are shown in Figure 4. The percentage values according to the vertical axis of the graph show the proportion of successful settlements in terms of the topic area within their settlement category. The horizontal axis shows the application topics.

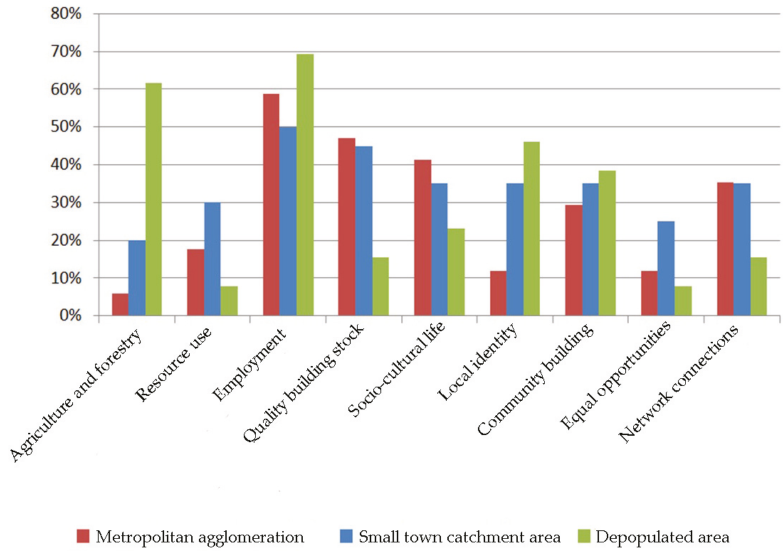

Figure 4. Development emphases depending on the role of the settlement network.

Based on the results, our main findings on thriving areas of village development are as follows:

- The need to develop employment is critical for all settlement groups. Employment is most important and productive in depopulated areas and agglomerations of large cities than in small towns.
- In addition to expanding employment, the villages of depopulated areas are the most successful in developing agriculture and forestry, while the settlements of the metropolitan agglomeration and small-town catchment areas are dominated by the quality development of the building stock.
- Community building and strengthening local identity is more successful in villages in depopulated areas (and small-town catchment areas) than in settlements around large cities.
- In the case of network connections, the lack of this is most pronounced in deprived areas.

3.2. International Outlook

Reviewing the applications in Hungary, the question may arise as to how the villages operate in the rest of Europe. In the case of European competitors, the analysis based on the settlement groups used in Hungarian villages is not necessarily expedient, as the administrative system of the settlement network in Hungary is completely different from the legal regulation of the Austrian, German, Swiss or Polish settlement system (administrative structure). In addition to the legal framework, the social differences of the last century and the natural geographical factors are also striking. At the same time, it is worth examining the results of some European competitors, because although we cannot obtain a comprehensive picture, we can gain insight into the general processes of wood-tree development.

To draw a parallel between the Hungarian applicants and the villages participating in the last European Village Renewal Award [48] we selected five German and Polish villages. We reviewed their applications: Dobkow (Lower Silesia, Poland) [51], Giersleben (Saxony-Anhalt, Germany) [52], Kadlub (Opole, Poland) [53], Rammenau (Saxony, Germany) [54] and Steinbach (Thuringia, Germany) [55]. A common feature of the villages was that they were located in the socialist bloc before the regime change. (Thus, in essence, their starting position is somewhat similar to that of Hungarian villages.)

Among the villages, according to a similar starting point presented above, further commonalities can be discovered:

- Before the start of village renewal, the villages all struggled with the difficulties of economic and social restructuring caused by the change of regime (closure of large farms, changes in agricultural ownership, resulting in unemployment, emigration, cessation of local services);
- Each of the villages belong to the catchment area of a medium or large city (Dobkow-Jelenia Gora; Kadlub-Opole; Giersleben-Aschersleben, Strasbourg, Bernburg; Rammenau-Bautzen, Dresden; Steinbach-Eisenach, Gotha), which has a significant extraction effect;
- Except for Giersleben, the villages both belong to the administrative area of a small town; thus, they do not have their budgets. This situation has accelerated the implementation of local developments and the strengthening of local identity;
- The starting point for the development was a consciously prepared, detailed development strategy.

Examining the development processes, the unique characteristics of each village can also be found, in addition to the standard features.

Located in Sudetenland, Dobkow (Poland) has based its development on local resources, highlighting all the elements of the project to present natural heritage: environmental awareness and harmony with nature in all areas of life (volcanic study trail, lectures emphasizing the importance of biodiversity, ecotourism developments, etc.). The other development priorities preserve built and cultural values: the renovation and recycling of typical buildings in Sudetenland (restaurant, accommodation, museum and education centre) and the preservation and passing on of traditions (beekeepers, potters, camps and meetings of traditional artists). These goals can be framed by a program called the "open-air eco-museum," in which local values can be visited through a village tour [51].

Kadlub's (Poland) primary strategic goal is to improve local care and expand local services through job creation and institutional development and a conscious community building that strengthens local identity. To achieve this, emphasis was placed on measures to set up businesses and create jobs; expand and improve the quality of services provided by educational, health and social institutions; expand the range of leisure activities; intensify intergenerational programs; and create new community opportunities and spaces (sports halls, cultural and leisure centres, outdoor sports centres and event space) [53].

Similar goals have been set in Giersleben (Germany), from which any major city is easily accessible due to excellent road and cable car transport. The main goals in the village are to increase the local standard of living (high-speed fibre-optic internet, quality social care for all ages, expand leisure activities), to ensure energy independence (wind farm), and to "save" the school as a community organizing force and development, strengthening the local civil society and strengthening gentle tourism [52].

Rammenau (Germany) has traditionally been an agricultural settlement, but this has only been a partial part of the main elements of the development strategy, because agriculture here (also) provides a livelihood for only a few people. (At the same time, agriculture also played an essential role in energy production through the built-in biogas plant.) The main development goals of Rammenau are job creation (an economic area for small businesses has been created on the outskirts of the village), strengthened tourism (fishpond, baroque castle, renovation of the built heritage—blacksmith shop, prison—utilization), creation of community spaces, community buildings and active civil life (civil house, village house event space, community space in the old smithy, many non-governmental organizations, regular events, etc.) as well as continuous education of environmental awareness from childhood and the use of renewable energy sources [54].

Steinbach (Germany), located in the mountains of Thuringia, has traditionally been an industrial village (there was a knife factory employing 1000 people in the GDR); thus, they had to face even more severe social and employment problems after the change of regime: 90% unemployment, 25% migration of the population, cessation of local shops and services. Therefore, the village has set up a joint development program with the neighbouring Bad Liebenstein, mainly to expand local employment (support small businesses: knife manufacture, brewery) and preserve tradition (cult of Martin Luther, a knife as a local symbol). As a high-quality locale, it focuses on the provision of health and social care[1], the development of community life (creation of community spaces, events), and the expansion of tourism (baroque castle, Europe-famous car race, Martin Luther cult, Steinbach knife) [55].

Reviewing the international examples, it can be stated that there are commonalities with the strategic development priorities of the Hungarian villages. However, the differences are also apparent, and the three groups of settlements defined in the Hungarian villages do not completely stand out in international cases.

As we showed in the introductory part of the paper, all foreign villages belong to the catchment area of a medium or large city, but when evaluating the strategies—compared to grouping the results of Hungarian village development strategies—some of them carry strategic elements of depopulated areas (e.g., Dobkow, Steinbach). Moreover, in the case of other settlements, the strategic elements of small-town catchment areas dominate (e.g., local identity, community building, resource use). The local identity and local community are more important in the villages located in the metropolitan areas than in the case of the Hungarian agglomeration villages. This may be due to:

- The different social customs and administrative situations in each country having created fundamentally different socio-economic situations, including different development priorities;
- Villages are mostly part of a small town (administration), and they do not have an independent decision-making body or an independent budget.

As a result of the above, the development based on independence and local society is a more vital driving force in all settlement groups than in Hungary. Thus, overall, these strategic priorities cannot be fully identified with the emphatic strategic elements of the Hungarian settlement groups.

3.3. Loss of Importance of Local Resources Based on Agricultural Land Use

The analysis of village renewal strategies in Hungary showed that (successful) developments based on agriculture and forestry as internal resources are present in only a tiny proportion of villages, with only a (smaller) share of local natural resources and land use prevailing, which determines the development priorities and strategic elements of villages. This is why we have reviewed the Hungarian village surveys of the last century and a half, focusing on the role of agriculture and forestry and the changes in the land use of villages.

During the land use surveys of the villages, it is worth reviewing the research that includes village surveys and village typifications. In Hungary, after the new millennium, these studies have mainly focused on the success of rural areas or the development of small village areas [33,37,56–58]. In addition to these, however, there are a large number of villages that either concentrated on a segment of Hungarian settlements [37,58–60] or conducted a nationwide survey [21,58,59]. It is interesting that during the typification of the villages, initially, the "external features" were decisive (morphology, size, population, form of farming), while later, they were due to the changes in the settlement network and the society, more complex indicators (living standards, nature of employment, population movement, development). Finally, village types were determined using complex statistical methods (cluster analysis, factor analysis).

In the present study, the villages were grouped in the manner defined in Section 2. Therefore, during the examination of the changes in land use, we are interested not in the changes in the village types but in the change in the classification methodology and the shifts in the development factors.

We have used five nationwide surveys of village research over the past 150 years, which are well differentiated over time. (The results of the first and second surveys were processed together.) Therefore, by ranking the results of the surveys, it is possible to show with well-defined characteristics how the aspects of the classification changed during each survey.

The first two surveys examined dates back to the time of the Reformation, the first was made by András Vályi[2] at the turns of the 18th and the 19th centuries [61], and the second Elek Fényes[3] in the middle of the 19th century [62]. Both works present the individual villages at the settlement level, giving a detailed description of the contemporary land uses, the quality of the land, and the crops grown.

In the 19th century, the natural endowments determined the possibilities of farming and thus of the given settlement. (In addition to the social and agricultural characteristics, the description of the villages in the examined villages highlights the location of only one castle, castle, inn or particular function.) Based on the works by András Vályi and Elek Fényes, the villages are considered as forest, meadow, vineyard, and livestock, with the simultaneous indication of unique local conditions (e.g., tobacco growing, vegetable growing, beekeeping, presence of a swell, castle or castle).

It was quite a long time, more than 100 years, until the date of the following national-level survey, which also determined the territorial characteristics, after the geographical dictionary (country description) of Elek Fényes in 1851. However, before the Second World War, the development of villages was still determined by agricultural conditions; thus, we cannot discuss more severe land use changes at the settlement level. (From Ferenc Erdei in 1940 entitled *Hungarian Village*, in his book, he separated the villages according to their agricultural ownership and social forms. In this idea, social aspects also appear in the grouping of villages. However, in Erdei's work, the village is still a type of settlement related to agriculture (peasant farming), and the typical peasant village is the "type of village that is usually cited as a village" [63]).

This situation was changed by the socialist takeover, which placed agriculture on a new footing and emphasised changes in the settlement network through industrial relocation and the reorganisation of agriculture. As a result, the status of settlements has entirely changed in many cases, and the results of this process are well illustrated by the work of Pál Beluszky[4] and Tamás T. Sikos[5] [64].

The authors aimed in their book (titled *Village types in Hungary*, from 1982) to examine the villages at the national level, assess and classify the condition of the villages, and differentiate the types of villages. (Regarding the changes in local resources and energy in the villages, despite the long time that has elapsed, the data from 1851 and 1982 can be considered successive periods in our study.) Therefore, the method of cluster analysis was chosen for the classification, during which eight groups of factors were identified:

- the natural environment of the villages;
- the place of villages in the settlement structure;
- the economic role of villages;
- the development of the role of the primary care provider in the villages;
- direction and pace of settlement development;
- the traffic situation of the villages;
- the artificial environment of the villages; housing;
- the level of the general development of the villages.

Based on the cluster analysis, the distinction between settlement types is based primarily on the occupational structure and on population change and/or settlement size. As a result of the typification, the research distinguishes seven village types (25 clusters) (Figure 5, Table 1).

Figure 5. Types of rural settlements in Hungary, 1982 [64].

In the characterization of village types (subtypes), the dominant economic sector plays a significant role, as shown by the names of the individual clusters (agricultural nature, agro-mixed functions, industrial municipalities, industrial-mixed and industrial-tertiary employment). It can be seen that the focus has shifted from land use to employment.

The next stage of our study is the analysis of the same pair of authors in 2007, the main aim of which is to present the changes of villages and the reclassification of village types at the beginning of the third millennium, especially after (and as a result of) the regime change [21]. As a result, the criteria for village classification also changed, during which seven main points and 27 variables were defined, as follows (number of variables in parentheses):

- land use, natural resources (1);
- the place of villages in the settlement structure (3);
- the economic role of villages (9);
- the traffic situation in the villages (1);
- basic provision of villages (2);
- the demographic and social situation of the villages, income and wealth relations (8),
- the pace and direction of settlement development (3).

As a result of the cluster analysis, the classification of village types is based on the role played in the settlement network, the labour market situation and the population change. The authors again distinguish seven village types (and 25 clusters) (Figure 6, Table 2).

Table 1. The name of the types of rural settlements in Hungary, 1982 [64].

Ordinal Number	Village Type Name	Clusters
I.	Small villages with a rapidly declining population, with no primary education, with unfavourable living conditions, with one-level functions	5, 8, 16, 20, 21, 22.
II.	Medium-sized villages with traditional village functions and agricultural (additionally industrial or tertiary) occupational structure	4, 6, 9, 11, 12, 15, 17
III.	Large and giant villages with mixed agriculture	3, 13
IV.	Centrally located, urban-type municipalities with an industrial-tertiary employment structure	25
V.	Population industrial villages, with a very rapid population growth, an urban environment, sometimes with an urban function	14
VI.	Rural settlements of agglomerations and residential areas	1, 2, 10, 18, 23, 24
VII.	Municipalities with special roles	7, 19

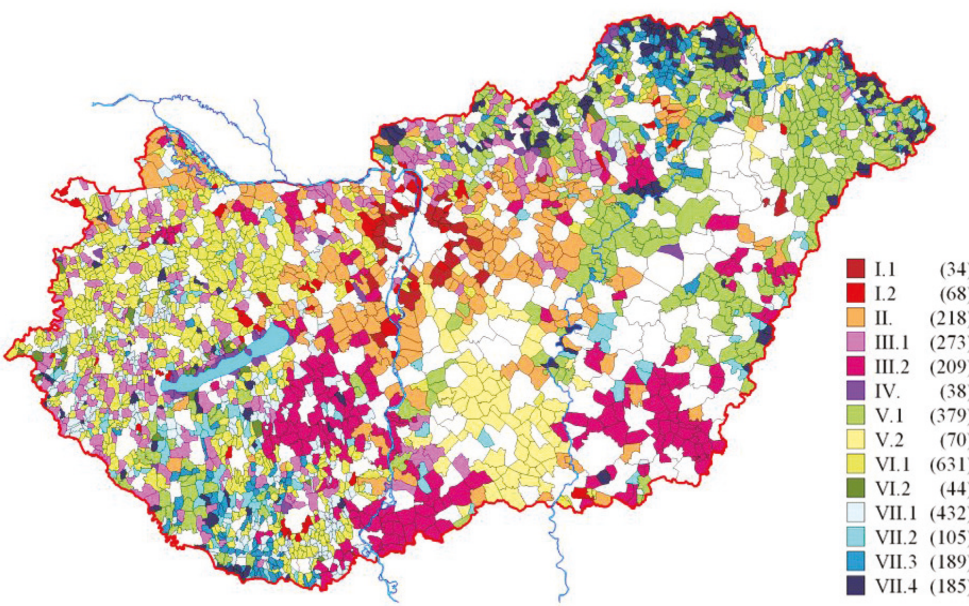

Figure 6. Village types in Hungary, 2007 [21].

Table 2. The name of the village types in Hungary, 2007 [21].

Ordinal Number	Village Type Name	Clusters
I.	Inner zone of agglomerations	1, 12, 17, 19
II.	Municipalities belonging to the outer zone of agglomerations	4
III.	Smaller, stagnant-moderately declining residential and mixed-use villages	14, 22
IV.	Villages and spas with a tourism role	6, 7, 9, 24
V.	Medium-sized villages with an unfavourable labour market situation, sometimes with a significant agricultural role or a peripheral population	15, 16
VI.	Small villages with a good labour market situation and a stable society, with a residential and tourism sector	8, 11, 18, 20, 25
VII.	Small villages with poor labour market situation, declining population, disadvantaged, distorted demographic-social structure (disadvantaged small villages)	2, 3, 5, 10, 13, 21, 23

Due to the socio-economic processes that took place after the regime change and the significant transformation of the settlement network, the emphasis on the separation of new village types is no longer on land use or employment stratification, but rather on demographic processes and the labour market situation. It can be stated that while earlier agricultural (later industrial) analysis dominated the clusters, after the turn of the millennium, the strength of the role of the residential function is the most crucial difference.

The last element of our analysis of the change in local resources is the national settlement cluster commissioned by the Ministry of the Interior, which was created in 2019 following the work of Miklós Illésy, Judit T. Nagy and Róza Számadó [65]. In this analysis, the authors divided the settlements into two groups: settlements with a population of over 2000 and less, and the statistical analyses were performed separately for the settlement groups. Cluster analysis was chosen as the classification method, using eight categories and 23 variables, of which the success criteria were cluster-forming variables.

The variables fell into the following categories:

- success indicators (criteria);
- demographic variables;
- variables measuring economic strength;
- variables measuring geographical location;
- variables measuring the development of the civil sector and cultural life;
- variables measuring the development of public service infrastructure;
- variables measuring the development of municipal co-operation;
- variables measuring the online presence of municipalities.

The cluster analysis resulted in three clusters for each settlement with less than 2000 inhabitants. The study summarizes the settlements with less than 2000 inhabitants under the collective name "small settlement", of which 2372 settlements belong to the clusters, and 781 settlements belong to the clusters with more than 2000 inhabitants. The names of the clusters are as follows (in brackets the symbol of the cluster and the number of settlements included):

- lagging small settlements (2000−/1; 1353 settlement);
- hybrid dwarf villages (2000−/2; 124 settlement);
- booming small settlements (2000−/3; 895 settlement);
- disadvantaged settlements (2000+/1; 341 settlement);

- settlements in the catchment area (2000+/2; 129 settlement);
- less attractive subcentres (2000+/3; 311 settlement).

Clusters are defined by the dynamics of the development of settlements. In addition to their role in the dominant network of settlements, economic, social and cultural aspects are essential. As a result, the results of the land use characteristics are minimal (almost non-existent).

4. Discussion

Based on the examination of the tender results of the Hungarian Village Renewal Award, we found that a close correlation can be observed between the development emphases and the distance from the centre settlements of the settlement network.

The conscious development of community buildings and local identity plays an increasingly important role in moving away from big cities. Accordingly, the development of these areas is more successful than in the villages of depopulated areas (and small towns). However, this is not the case in the settlements of the metropolitan agglomeration because, although financial resources are available, due to the different needs of a diverse society, in most cases, we cannot speak of a classical community; thus, in many cases, in short, they focus on improving the quality of life. A similar trend is valid for the utilization of network connections. This is not strong in any of the settlement groups. However, the majority of network connections typically represents the connection to the centre settlement (villages have only fewer network connections); thus, it is clear that small settlements closer to the nodes of the settlement network are more active in using these opportunities. The strengthening of local society and local identity is present with great emphasis everywhere when examining international examples. Therefore, it is not valid in the studied countries that this is less important in the vicinity of big cities.

In the study of village renewal strategies, the loss of space for developments based on agriculture and natural resources was noticeable; thus, we examined which factors were emphasized in previous research to determine the types of villages and which development elements became cluster-forming variables. It has become clear that the role of (agricultural) land use is becoming less and less important over time. One hundred fifty years ago, settlements were defined by their status and land use; thus, land use was the basis for grouping in the surveys. In the 20th century, agriculture surveys were first reduced to a "yes/no" question and were then refined into a weightless variable.

Examining the variables (and clusters) of the surveys, it can be stated that the importance of the previously decisive role of land use (initially agricultural and later industrial) in the life and development of villages was taken by the proximity of employment, the role of settlement networks and network priorities. In all this, it can be traced that among the variables of the national surveys analysed in our surveys, more and more indicators have emerged that have analysed the economy and development (or success) of the village.

Overall, we found that the choice of the settlement development strategy is greatly influenced by the situation of the settlement network, the available (internal and external) resources and the internal motivation. Different settlement development strategies can both lead to success, but the role of the settlement network fundamentally influences the opportunities. For example, while the villages of large urban agglomerations and small-town catchment areas can be successful with the proper use of situational energies, a successful development project based on internal resources can stand out from similar settlements. Conversely, settlements have to face unfavourable settlement processes in depopulated areas. This is because the implementation of a successful development strategy in these villages and the realization of favourable development dynamics must always be based on internal resources. That is why in the latter group of settlements many so-called "separate" development strategies and, in the absence of other options, agricultural-based (or other local resource-based) developments are still of strategic importance.

The novelty of our research is that, regardless of the current state of the villages, we grouped the villages based on the goals and priorities of the development strategies. While some of the previous studies sought to examine the situation of villages and possibly typify them, others examined the success of small settlements by examining a smaller group of settlements. In the present research, we focused on defining strategic priorities depending on the settlement network situation.

5. Conclusions

Our article wanted to examine the village development strategies and analyse and evaluate the strategic directions, primarily through the examples of Hungarian villages that participated in the Hungarian Village Renewal Award competition. To understand the objectives of the village development strategies, it was essential to take into account the changes in the Hungarian settlement network and the changed village roles, as well as to become acquainted with the most important goals of the Hungarian and European Village Renewal Award and the competition qualification system. Therefore, we carried out its research by analysing the applications of 50 Hungarian villages, examining how each element of the village renewal strategy relates to the settlement network's role and the distance from the centre settlement.

A significant result of our research was the definition of three groups of settlements according to the position of the villages in the settlement network. After analysing the groups, we found that the villages set different development priorities in terms of the role of the settlement network. Therefore, the villages of each settlement group have a strategy based on different development directions. In the vicinity of large- and medium-sized cities, which are the focal points of the settlement network, development areas for improving the quality of life (e.g., quality building stock, socio-cultural life) dominate, and employment is the most critical area in urban areas, but also strengthening local identity and community building.

Our studies have highlighted the role of agricultural land use in village development strategies. Although agriculture is still an essential aspect of the development of depopulated areas, it is worth considering that the agricultural land is a significant development priority in only a group of villages, serving an increasingly small section of society.

The main goal of our research was to help the villages to survive, renew and develop through the analysis of strategies. To this end, we examined in detail the development measures and strategies of the villages. By arranging the information, we tried to achieve a result that could be used in practice. Based on these, we recommend:

- to provide as much information as possible to the rural municipalities to explore the local conditions more precisely and make a conscious strategy;
- to adapt the support framework of the existing tender resources (with the related indicators) to the villages' groups according to the settlement network's role. Thus, targeted subsidies corresponding to different development priorities would be available to the villages of each settlement group.

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Appendix A. Motto and Winners of the European Village Renewal Competitions

Table A1. Motto and winners of each competition.

1990: International exchange of experiences	Dorfbeuern I Salzburg I Austria
1992: Being there is everything	Illschwang I Bavaria I Germany
1994: Own initiative is trump	Steinbach an der Steyr I Upper Austria I Austria
1996: Comprehensive village renewal	Beckerich I Luxembourg
1998: Creative-innovative-cooperative	Obermarkersdorf I Lower Austria I Austria
2000: There is no past without future	Kirchlinteln I Lower Saxony I Germany
2002: Crossing borders	Großes Walsertal I Vorarlberg I Austria
2004: Meeting the challenge of uniqueness	Ummendorf I Saxony-Anhalt I Germany
2006: Change as opportunity	Koudum I Netherlands
2008: Win the future through social innovation	Sand in Taufers I South Tyrol I Italy
2010: New energy for a strong togetherness	Langenegg I Vorarlberg I Austria
2012: On the track to the future	Vals I Grisons I Switzerland
2014: Lead a better life	Tihany I Veszprém I Hungary
2016: Open mind	Fließ I Tyrol I Austria
2018: Th!nk further	Hinterstoder I Upper Austria I Austria
2020: Local answers to global challenges	Municipal Alliance Hofheimer Land I Bavaria I Germany

Notes

1 Health and social care facilities are available in Bad Liebenstein and are provided by mobile public transport, e.g., E-car, E-carriage, village bus.

2 Hungarian statistician, geographer, teacher, professor at the University of Pest.

3 Hungarian statistician, writer of economic statistics and geography, member of the Hungarian Academy of Sciences.

4 Researcher (regional sciences), university professor. His main field of research is the historical and settlement geography of Hungary.

5 Researcher (regional sciences), university professor. He specializes in marketing geography.

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Land Take Processes and Challenges for Urban Agriculture: A Spatial Analysis for Novi Sad, Serbia

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Abstract: Food security is becoming an increasingly important issue worldwide, and in this respect, urban agriculture has a substantial role. Nonetheless, pressure for agricultural land conversion and fragmentation is highest in peri-urban areas. In order to respond to these challenges, urban farmers use different adaptation strategies and business models, including product differentiation based on geographical indications (GIs). The paper considers land take (LT) issues in Futog, the settlement of the City of Novi Sad, registered as the GI of *Futog cabbage*, as an illustrative example which reflects the attitude of land use policy and planning in Serbia towards the specific conditions and requirements that growers of GIs have to meet. The purpose of this study is to identify the role of urban land use planning within LT processes and the implications this has on urban agriculture, accordingly. The supporting framework used for quantifying LT in the period 2000–2018 was CORINE Land Cover (CLC), specifically Urban Atlas (UA) datasets for two time series between 2012 and 2018. Since a significant part of agricultural land registered as a GI in Futog was planned for conversion into construction land, the authors conclude that current forms of land use planning in Serbia are not adequate to ensure the protection of either urban agriculture or GIs. Given that there is a clear correlation between GI products and their place of origin, this study recognized the necessary inclusion of all protected agricultural areas, as well as areas with GIs, into legislation binding for land use planning in Serbia, with limitations in terms of new LT.

Keywords: land take; urban agriculture; land use planning; zoning; GI products

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1. Introduction

Faced with rapid urbanization, changing consumer preferences, and a series of financial, health, environmental, and political crises that affect global food supply chains, those in academia, urban planners, and decision-makers are becoming increasingly aware of the multiple benefits that urban agriculture provides in strengthening urban resilience and global sustainability [1–3].

Urban sprawl is considered to be the main result of land use changes due to urbanization in Europe [4]. It specifically describes the scattered development of settlements in the peri-urban area [5] and it is quantified by the monitoring of land take (LT). Mainstream European policies on land use suggests that all EU-members should stop the process of LT by 2050 ("no net land take") (i.e., to prevent construction and soil sealing at the expense of agricultural land, forestry and other natural areas), otherwise, any new LT will need to be compensated by the reclamation of artificial land [6]. It is recommended that resources are allocated in order to better protect agricultural soils [7]. On the other hand, Europe is expected to be home to nearly 85% of urban residents by 2050 [8], and its sustainable development will increasingly depend on the successful management of urban growth and rural–urban linkages, which is in line with UN Sustainable Development Goals (SDG); indeed, Goal 11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable [8,9].

Concerns over food security have given rise to various initiatives for applying land use planning to protect urban agriculture from urbanization processes [10]. For that purpose, zoning ordinances are used as a typically regulatory mechanism to minimize conflicting uses on agricultural land [11–19]. In order to match various urban pressures on farming, and to strengthen its resilience, different urban farming business models are promoted [20–23], including product differentiation based on geographical origin [24,25]. Urban planners and municipalities in several European countries developed strategies to protect urban, and particularly commercial, peri-urban agriculture in metropolitan areas. [26,27]. Researchers confirmed the existence of a zone of urban farming that is covered by some forms of controlled urbanization, running from the Benelux countries to Italy, which is capable of responding to new societal demands regarding food and agriculture [28]. At the same time, urban farming in Eastern Europe lags behind its western counterpart in the sense that farming, which is developed, is also "non-urban adapted" [28] (p. 17).

The above conclusion could also be valid for Serbia, particularly in terms of agriculture in its largest metropolitan area, which consists of Belgrade and Novi Sad functional urban areas (FUAs). This metropolitan area encompassed 5032 km^2, and had an estimated population of 2.1 million inhabitants in 2020 [29]. Urban agriculture has an important role in supplying the Belgrade–Novi Sad metropolitan area with fresh food for city markets, the food industry, and for export [30]. Intensive, non-urban adapted crop production and livestock farms, modern orchards, and the food industry, adjusted to the mass market, still comprise the sector's backbone; however, an increasing number of usually smaller and medium-sized farmers adopted (a mix of) different urban farming business models, and they use the higher purchasing power of urban consumers for direct marketing and the sale of value-added foods, often in combination with on-farm services [22,31]. Recently, the intention to renew and strengthen the 2010 project of supplying Belgrade with healthy and fresh food by placing Belgrade Green Ring farms around Belgrade has been announced [32].

At the same time, urban agriculture and farmers are facing strong LT pressures throughout the metropolitan area. The focus of this paper is on the recent LT case within Novi Sad FUA, with the purpose to identify the role of urban land use planning within LT processes and the implications on urban agriculture, drawing on Futog, the settlement in the peri-urban area of Novi Sad, as a case study. The urban agriculture of Novi Sad FUA is very specific, regarding the variety of food and drink products with GI protection in its territory. The Futog area is distinctive due to the production of *Futog cabbage*, which is a vegetable that is registered with the Appellations of Origin (AO) of Serbian Intellectual Property Office (IPO). Taking into account such a particularity of the study area, the objective of the research is to examine the ability of land use policy and planning in Serbia to comply with the specific conditions and requirements of the GI product urban growers. The leading questions are: in what manner, and to what extent, do urban land use planning practices influence LT, and how is that reflected in a specific urban agricultural environment. In order to present the research framework, the next section is dedicated to reviewing the literature that is relevant to the LT and urban agriculture analysis.

2. Literature Review

Worldwide, researchers are attempting to describe the phenomenon of the conversion of agricultural land to urban uses. Land use change due to urbanization processes is one of the most common phenomena and one of the main drivers of global environmental change. In that sense, due to urbanization affecting Europe, urban sprawl is recognized as one of the most important types of land use change [4], and it is related to the physical pattern of the low-density unplanned expansion of large urban areas, mainly into the surrounding agricultural areas [33].

The impacts of urban sprawl are often quantified by monitoring land take[1] (LT) or soil sealing indicators [35], and across the European Union, those indicators are monitored by the European Environment Agency[2] since 2004. LT is the loss of agricultural land, forests, and other semi-natural and natural land to urban and other artificial land development [33], which manifests as an increase in artificial surfaces over a time period [36]. Precise methodology for quantifying urban land take is still subject to scientific debate, mainly because the variability of the term "urban agglomeration", which can have different geographic boundaries depending on the scales (e.g., the city proper, the metropolitan area, urban cluster or the urban agglomeration) [37]. LT in EU28 was 539 km^2 p. annum, whereas the overall annual loss of undeveloped land to settlement and infrastructure development is more than tenfold the area that is cultivated again, and was observed during 2012–2018 [38].

In the context of spatial planning, LT and land consumption are, in many cases, used interchangeably, but Marquard et al. [39] suggested prioritizing the term "land take" in the EU context. Evers et al. [40] rejected terminology such as "land take" and "sprawl", concentrating instead on the (dis)advantages that divergent modes of urbanization can have for sustainability in its broadest sense[3]. Land use planning is considered as "sufficiently comprehensive, binding and restrictive" to contribute to a reduction of LT [34] (p. 349). There is a consensus that "spatial planning influences patterns of land use and land cover" (Couclelis, 2005 according to [41]), whereas some studies recognize land-use policies and spatial planning as a fundamental driving factor for many different land-use change processes[4] [41] (p. 32).

There is a consensus that urban agriculture improves the environment, landscape, and quality of life of urban dwellers, and that it contributes to food security, employment, and social cohesion [1–3,43]. It is important for local identification and societal interaction through local products, traditional production practices, landscape protection activities and seasonal events, but on the other hand, pressures for agricultural land conversion and fragmentation are strongest in peri-urban areas [44]. Since the future for most of the global population will be urban, and as soil sealing corresponds with rapid urbanization, integration between spatial and agricultural planning policies is increasingly important for the prevention of conflict [45,46].

Traditional planning tools, such as zoning regulations, development control, urban growth boundaries and green belts, as well as other tools for land use control (development fees, infrastructure financing, financial incentives etc.) traditionally represent the main planning instruments for urban agriculture preservation [11–18]. In practice, transferable development rights programs can be implemented to address different land preservation/development objectives [47]. Planners use these market-based instruments to achieve land preservation goals, whilst tackling the issues surrounding urban sprawl [48].

Urban pressures on farming, including land competition as well as urban opportunities related to the proximity of knowledge and innovations, have promoted the development of different urban farming business models, strengthening its resilience [20–22]. Van der Schans et al. [23] identified five business strategies as an outline for innovation in urban agriculture: low cost, differentiation, diversification, the commons, and experiences. Differentiation involves high-value local, organic, or traditional foods as well as vertical integration processes in which additional value is added to a product via processing, distribution, and direct sales [23]. Value can be added to the products through GIs as well, as indications of their geographical origin and quality, or in terms of their reputation, which can be attributable to that origin [25]. Compared with diversified peri-urban agriculture that requires more flexibility in policy and planning in responding to multifunctional land use dynamics [12,49], GI products encourage the adoption of stricter, long-term land protection strategies since the land is essential for their business success [50]. It is also necessary for the state to financially support GI dynamics, design a framework for raising producers' awareness of GIs, and facilitate their collective involvement in GI governance [51].

The SDGs encourage a substantial increase in food security to achieve zero hunger and promote sustainable agriculture (SDG 2) while minimizing the conversion of undeveloped land into developed land (SDG 11). SDG 11 calls for inclusive, safe, resilient, and sustainable cities, and it covers the spatial aspect of urbanization with its indicator of land consumption. SDG target 11.3 presents the dynamics of LT per person and aims to achieve an increased rate of built-up land that does not exceed the rate of the increase in population [9]. On the other hand, a recent extensive study suggests that built-up land change trajectories provide the basis for a better understanding of urbanization processes across the globe [52], and they indicate that progress towards SDG target 11.3 should consider changes on smaller spatial scales [Ibid.], as well as ones at the global level. One of the study's main arguments is that the process of increasing the share of the population living in urban areas, in itself, is not necessarily unsustainable from a LT point of view, because built-up land in large, small, and medium city centers is used more intensively over time [52] (p. 10).

Gardi et al. [53] proposed a methodology to quantify the impact of LT on food security at the European level, and demonstrated that LT could be an important threat to food security from a long-term perspective.

Policy makers must combine regulatory protection with positive reinforcement of farming activity to support agricultural land use [54], although land use planning occasionally fails to encourage farmers to continue their agricultural activities near urban areas, which results in the abandonment of agricultural activities [55]. Agricultural development plans can play an important role in land use management and in the promotion of the added regional value of urban agriculture; however, more integrated urban food policies are needed to recognize its cross-sectional nature [56]. Territorial governance, as a means through which spatial plans are prepared and implemented, is a complex set of interactions, rather than just broad objectives formulated into regulations and building permits related to land-change [41]; however, if local policy is unclear and regulatory frameworks for urban food production do not consider its specificities, it is likely to reduce the potential business success of urban farmers [57,58].

3. Materials and Methods

3.1. Study Area

Novi Sad is the administrative center of the Autonomous Province of Vojvodina in the northern part of Serbia, the second largest city, and an important urban center in Serbia. In addition to Novi Sad, other larger settlements are located in its vicinity, and the concentration of the population is the result of urbanization processes, which have taken place in recent decades [59]. Recent studies, which include indicators such as commuting and employment, show that the urban influence of Novi Sad exceeds its administrative boundaries [60]. The FUA of Novi Sad encompasses 1892 km^2 and had an estimated population of 460,737 in 2020 [29]. The utilized agriculture area covered 114,083 ha of this territory in 2018 and includes 105,298 ha of arable land, 2716 ha of orchards, 871 ha of vineyards, and 4839 ha of meadows and pastures. There were also 63,773 livestock units on the farms. Farmers on 13,399 farms realized a average standard output (SO) per farm of EUR 12,613, compared with EUR 11,379 in the Belgrade FUA, and EUR 8642 at the national level. Farms with other gainful activities achieved an average SO per farm of EUR 27,481, compared with EUR 13,096 in the Belgrade FUA, and EUR 11,116 at the national level [61]. In the northern and eastern lowland part of the area, intensive production of cereals and oilseeds dominates, and the country's largest organic dairy farm is also located there (in Čurug). The peri-urban area of the city of Novi Sad is known for its production of value-added vegetables and ethno-tourist farms ("salaši"), whereas the slopes of Fruška Gora Mountain are covered by orchards and vineyards with a number of family-owned vineries on the Danube Wine Roads [30,31].

Organically produced grain and industrial crops for processing, as well as organic milk, beef, fruits, vegetables, honey, medicinal plants, and spices, have good sales prospects in the market niches of the metropolitan area [62]. The urban agriculture of the Novi Sad FUA has another specificity—several food and drink products with GI protections for its territory; for instance, Bermet, which is an aromatized wine (Serbian IPO AO, 2007, WIPO AO, 2011), Riesling from Karlovac (Serbian IPO AO, 2008) in the vine region of the Fruška Gora mountain, lime tree honey from Fruška Gora (Serbian IPO AO, 2011), carrots from Begeč (Serbian IPO GI, 2017), and fresh and sour cabbage from Futog (Serbian IPO AO, 2008). The latter product is from the production area which is the subject of the following case study [63].

Futog belongs to the western group of settlements of the city of Novi Sad, and after Novi Sad, it is the second largest settlement; in 2011, around 6% of the total population of the city lived there [64]. Futog develops on the alluvial terrace of the Danube River. Fertile agricultural land, plenty of water, and proximity to large metropolitan markets, makes Futog a good prospect for competitive urban agriculture (Figure 1).

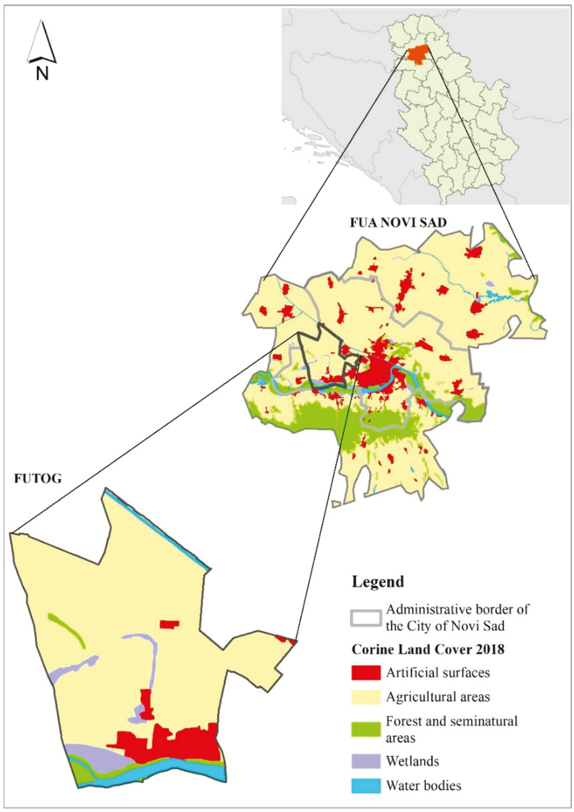


Figure 1. Location and land cover characteristics of the study area.

The AO *Fresh and sour cabbage from Futog* was registered in 2008 by the Serbian Intellectual Property Office (IPO), and according to the decision on the registration, it is produced exclusively in the area of the cadastral municipality of Futog ("Futog atar") [63]. The first certification was carried out in 2012 and in 2014; the *Futog cabbage* production area was about 22.26 ha, with a production of 468 tons. Following certification, a significant AO-linked price increase for fresh and sour cabbage was observed in all distribution channels. Consumers, who were already familiar with the good reputation of the traditional *Futog cabbage* variety, have accepted paying a higher price for AO cabbage. Production of the AO cabbage also has positive effects on the non-AO cabbage value chains. The cabbage fair (*Kupusijada*) serves traditional dishes to visitors, which contributes to tourism development [65]. In 2020, there were 40 producers of the Futog AO cabbage, including one organic producer and one processor–producer of sour cabbage [66]. According to 2021 data, 27 producers grew certified cabbage on 35 ha [67].

3.2. Data Collection, Analysis and Methodology

CORINE Land Cover (CLC) is one of the most common land cover data sources and is widely used in spatial research across Europe. Despite many advantages and possibilities for interpretation and analysis, limitations in the application of the CLC database have also been noticed. Most of the limitations are related to the low level of detail of anthropogenic classes, which is sometimes not enough for precise modelling; for example, in models of spatial distribution concerning population, urban land use dynamics, and so on. [68–70]. This is particularly visible in small scale units (e.g., settlements), which is hard to detect as the Minimum Mapping Unit (MMU) for areal phenomena is 25 ha and the minimum width of linear elements is 100 m [39].

In this research, we used data available in Urban Atlas (UA). UA is a joint initiative of the Commission Directorate-General for Regional and Urban Policy and the Directorate-General for Defense Industry and Space (DEFIS), which are part of the EU Copernicus program, and they have the support of the European Space Agency and the European Environment Agency [71]. UA contains data concerning land use, which are integrated with population estimates for European cities with a population of more than 50,000 inhabitants and their gravitational areas (Functional Urban Areas–FUA). The FUA consist of a city and its commuting zone [72]. UA classification includes 27 classes arranged in 5 levels, where each of them describes different land cover. Data are grouped into five basic classes: (1) artificial surfaces; (2) agricultural areas; (3) natural and semi-natural areas; (4) wetlands; and (5) water. Currently, data are available for three time series 2006, 2012, and 2018. The layer from 2006 covered large urban zones from EU member states, whereas series 2012 and 2018 included FUA from EFTA countries, such as the West Balkans and Turkey. In addition, two layers of change are available from 2012 [71].

In comparison to CLC data, UA data have better spatial resolutions, with a focus on urban areas. UA is supplemented and enriched with additional information from various available data sources such as High-Resolution Layer (HRL), Open Street Map, Google Earth, and so on. [73]. The MMU for the UA is 0.25 ha for surface objects of class 1 and 1 ha for classes 2 to 5. It means it has a 100 times greater resolution compared to CLC datasets [74]; therefore, this dataset enables the monitoring of land use with a high level of accuracy.

In order to avoid misconceptions regarding definitions of urban agglomeration [37], this research has used boundaries for FUA in Novi Sad from the UA dataset. FUA in Novi Sad covers an area of 1892 km^2, which is significantly larger than the administrative area of the city of Novi Sad. This research uses UA data in vector format for two time series, 2012 and 2018, which are available for Serbia (Figures 2 and 3). Land take is defined as the change of land from agricultural land, forests, natural and semi-natural areas, water, and wetlands to build up land in Novi Sad FUA. The analyses include aggregation of all artificial classes from the UA database at the fourth level of detail sub-classes 11100, 11210, 11220, 11230, 11240, 11300, 12100, 12210, 12220, 12230, 12300, 12400, 13100, 13300, 13400, 14100, and 14200. The list and details of all classes can be found in the UA guide [73].

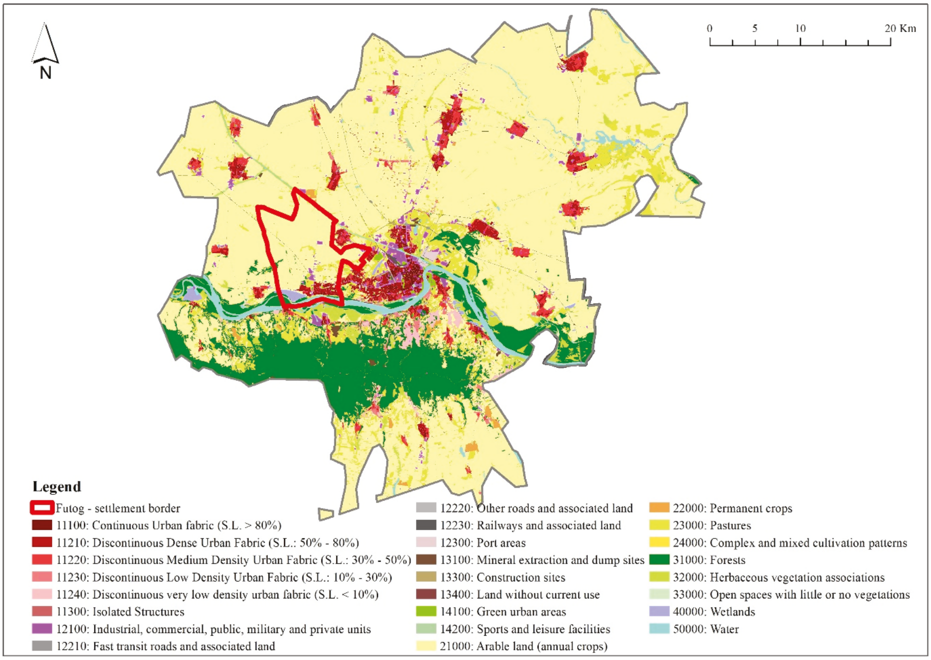


Figure 2. Land cover for Novi Sad FUA (2012).

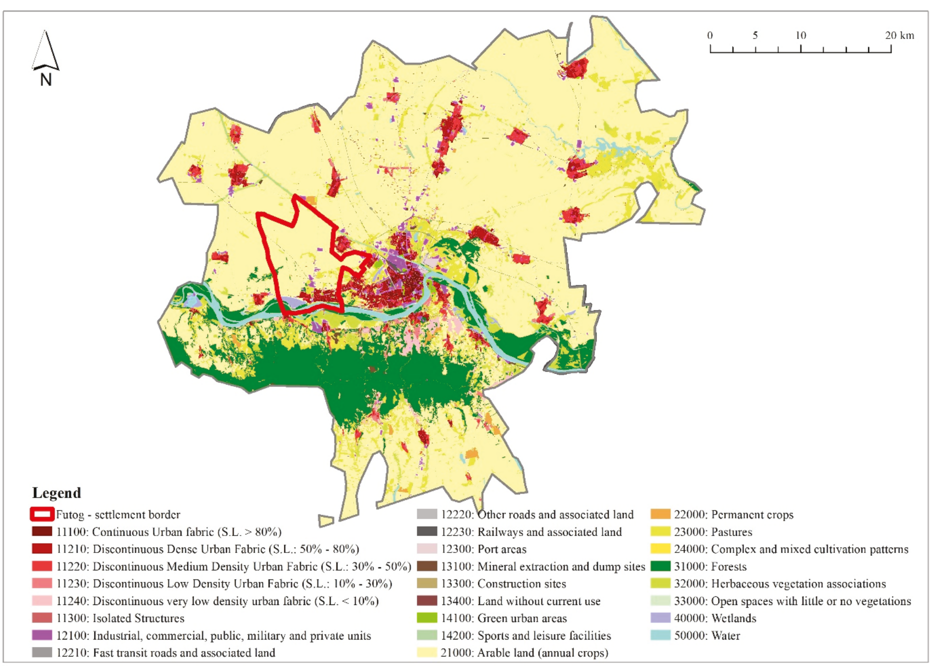


Figure 3. Land cover for Novi Sad FUA (2018).

In accordance with the SDG indicator 11.3.1, the land consumption rate is defined as "the percentage of current total urban land that was newly developed" [75]. Here, it is acknowledged that the methodology for the calculation of the land consumption rate for SDG indicator 11.3.1 is still a subject for scientific debate (cf. [39]); however, as it is sufficiently credible, we adopted the calculation [39,75] of the land take rate (LTR) as follows:

$$LTR = \frac{\ln\left(\frac{Urb_t + n)}{Urb_t}\right)}{(y)}$$

where:

- ln = Natural logarithm;
- $Urb_t + n$ = Surface occupied by urban areas in km^2 in the final year;
- Urb_t = Surface occupied by urban areas in km^2 at the initial year;
- and y = the number of years between the two measurement periods.

In addition, statistical data were used in order to obtain socio-economic structures of the farming community in Futog.

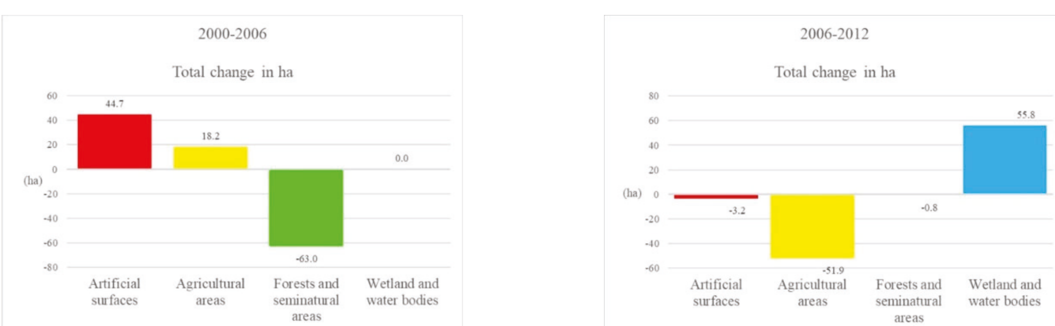
4. Results

Table 1 shows the types and proportion of land use in the Futog settlement in the period 2000–2018. Agricultural land is the most distributed land use type, and wetland and water bodies comprise the second one. As shown in Chart 1, in the period 2000–2006, forests and semi-natural areas underwent the highest levels of conversion (−63 ha), and until 2018, that was the only conversion of this land use type. In the period 2006–2012, the loss of agricultural areas underwent the highest level of conversion (−55 ha); however, when including the previous period and the increase in agricultural land, the overall loss of agricultural land was 34 ha.

Table 1. Land use dynamics in Futog between 2000–2018.

Land Use Type	Year 2000 (ha)	Year 2018 (ha)	Total Change–Land Take (ha)
Artificial	591	633	42
Agricultural	6776	6742	−34
Forests and seminatural areas	273	210	−63
Wetland and water bodies	686	741	55
Total	8326	8326	-

Source: Authors' calculation based on [76].



(**a**) (**b**)

Chart 1. Land take (ha) in Futog for the period (**a**) 2000–2006; (**b**) 2006–2012.

For the period 2012–2018, CLC datasets resolution had not detected any land cover changes.

Urban plans are predominantly aimed at managing land use in urban areas in Serbia. According to the Constitution of the Republic of Serbia Article 190, urban planning is originally one of the competences of the local self-government. One of the basic instruments by which land use planning protects the environment, and also the public interest, is land use zoning. According to the umbrella law for land use planning issues (Law on planning and construction) [77], general regulation plans are to be adopted for the entire construction area of the settlement, by parts of the settlement. This is the basic regulation plan that is directly implemented by applying regulations and building rules for the entirety of the planning document. The general regulation plan, in particular, the designated building zones, contains the division of the area into separate units and zones (zoning).

Therefore, here is the analyzed General Regulation Plan (GRP) of the Futog Settlement [78] and its subsequent amendments [79], which were implemented between 2015–2021. The basic concept of spatial development within the General Regulation Plan of the Futog Settlement creates the conditions for arranging the area of the rural settlement of Futog ("atar"), primarily as an area of agricultural production and building zones (Table 2). Agriculture is considered as a primary activity which also supports the preservation of existing forest areas (and the afforestation of new ones), pastures, ponds, reeds, and marshes, as well as the reconstruction and revitalization of ethno-tourist family farms ("salaši").

Table 2. Planed land use balance for the Futog settlement 2015–2021.

Land Use	Area (ha)	%
GRP	**8280.85**	**100**
Building zone of Futog	**1087.62**	**13.13**
Public land use	**463.37**	**42.67**
Central and communal function	69.71	6.23
Education	62.41	5.74
Health care	3.79	0.35
Greenery/forestry	76.40	7.26
Traffic	224.06	20.60
Hydrotechnical infrastructure	27.00	2.49
Other land use	**624.25**	**57.33**
Housing	410.58	37.75
Tourism	6.89	0.52
Business	206.78	19.06
Futog "atar"	**7183.23**	**86.87** *

* Source: elaborated by authors based on [78,79].

About 72% of the active population of Futog is employed in business, most of them in the processing industry and trade. Businesses are located within and outside the building zone of Futog, in working zones, at the entrance directions to the settlement and within single-family housing plots. For the purpose of equipping the community, expanding the building land in the rural settlement of Futog ("atar") is planned, within the area planned for businesses, in terms of entrance directions to the settlement.

In addition, for a long time, the area that was not intended for construction, particularly residential construction between the building zones of Futog, Veternik, and Novi Sad, had been taken over with the illegal construction of residential and cottage buildings; therefore, the city renounced its earlier plans, according to which, the area between the city and the closest settlements should have been preserved as agricultural land, as well as for developments that could have a regional and wider importance [80]. During 2021, an initiative for the additional expansion of building land in Futog was submitted again, with new Amendments to the plan of the general regulation of Futog settlement [81], with planned LT volume of more than 15 ha at the expense of the agricultural land of 'atar'.

Concerning the quantification of LT in Futog in the previous period, in order to obtain measurable and comparable data, the information layers concerning land cover, obtained from the UA dataset within the administrative area of the Futog settlement, were imported into the GIS environment.

The obtained results show that in the FUA of Novi Sad, the percentage of LT is not high and counts for less than 1%. The total area of agricultural land decreased by around 1 km^2 in the observed period. Forest areas show a reduction of the same levels. Similar trends are present in the Futog settlement. According to UA data for 2018, agricultural areas with arable land cover dominating the largest surfaces in the Futog settlement (81%). Artificial surfaces cover around 9% of the total settlement surface with discontinuous dense urban fabric dominating, with an average degree of soil sealing between 50–80%. These areas cover about 51% of the total artificial surfaces. Other classes (forests, natural and semi-natural areas, wetlands, and water) cover around 10% of the total settlement surface. The LTR is 0.00492, which implies that the share of urban (built-up) areas have increased by 0.5% between 2012 and 2018. These changes are mainly related to the reduction of arable land in favor of discontinuous dense urban fabric and industrial, commercial, public, military, and private units. Figure 4 illustrates land cover in the Futog settlement in 2018, together with detected land take areas. Although the observation period is not long, the results indicate the existence of the land take process in the Futog settlement.

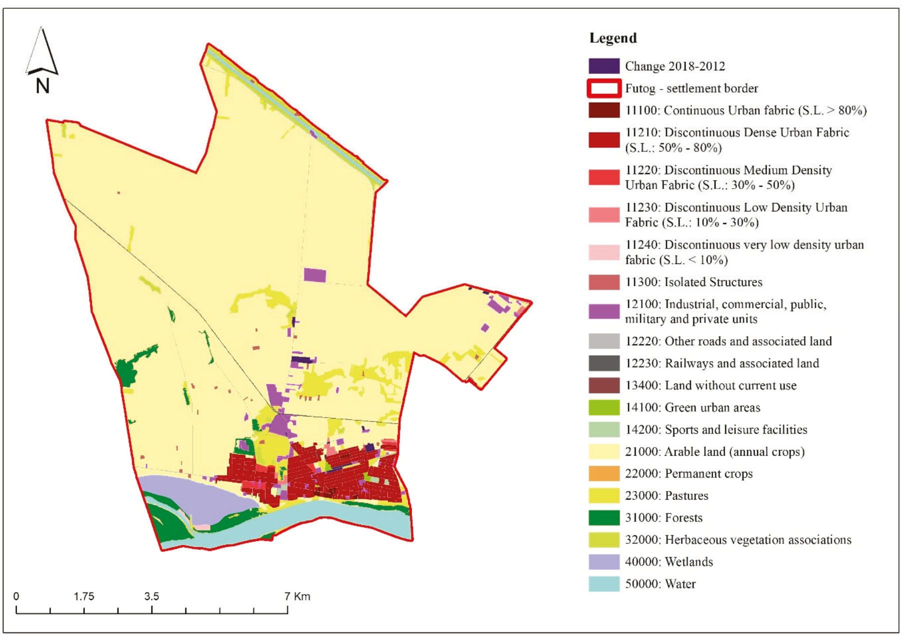


Figure 4. Spatial distribution of land take in the Futog settlement for the period 2012–2018.

Regarding capacities for urban agriculture, according to the 2012 Census of Agriculture [82], 461 family farms, 6 farms of legal entities, and unincorporated enterprises in Futog, had 2346 ha of land, owned or leased, of which 2299 ha comprises a utilized agricultural area. Arable land covered 2260 ha and was being cultivated by 411 farms. Half of that arable land is used for cereals, 28% is used for industrial crops, 11% is used for vegetables, melons, and strawberries, 6% is used for potatoes, and 4% is used for fodder crops. Vegetables, melons, and strawberries were grown by 144 farmers on 248 ha of arable land. Although 238 out of a total of 467 farmers are engaged in livestock breeding, this production is concentrated in a small number of larger farms. Food processing involved 19 farms, of which nine processed fruits and vegetables.

Cabbage and kale were the most common vegetable crops and covered 205 ha [82]. Many cabbage growers remained faithful to the native population cultivated in Futog since 1760, and it is highly valued due to the specific qualitative properties of its leaves. As seen earlier, this cabbage has a registered appellation of origin and production area that exclusively encompass the cadastral municipality of Futog [63].

5. Discussion

In Serbia, proper use of agricultural land is a task that concerns effective mechanisms for controlling the implementation of spatial planning and zoning measures [83]. Those measures should prevent the excessive conversion of fertile land to non-agricultural purposes [Ibid.]. Creating an efficient system of land resource management is among the priorities of the national agricultural policy [84]. According to the Law on soil protection [85], spatial planning, and the use of natural resources and goods in accordance with spatial, urban, and other planning documents, prevents land degradation. The Law on agricultural land [86] makes a distinction between the different uses of agricultural land in terms of its quality, and in that sense, it is forbidden to use an arable agricultural land up to the fifth cadastral class for non-agricultural purposes, except in cases where the public interest is determined by law and with compensation for land use change. On the other hand, according to the Law on planning and construction [77], agricultural land which changed into building/construction land via the planning document, can be utilized for agricultural production until the land is brought into its planned use. From the point of view of property tax, such land is construction land, and the owner of such land is obliged to pay a fee for changing the purpose of the land before issuing a building permit (developer obligations, i.e., indirect value capture).

Although agricultural land is, nominally, one of the most important natural resources in Serbia, it must be noted that in the previous period, there was a planned tendency to reduce the number of agricultural areas in the long-term, which was shown by the quantitative analysis of land planning and management at the local level [87]. According to [88], the value of construction land in the Republic of Serbia increased about 1.000 times compared with its initial, original value as agricultural or forest land; therefore, it was converted into construction land. Agricultural land is highly attractive for investors/developers, especially if it is illegal. Illegally built and undeveloped peripheral urban zones (urban sprawl) directly correlate with the conversion of agricultural land into construction land, regardless of the category and quality of soil (e.g., Bangladeš, which was one of the informal settlements in Futog) [89]. Qualitative research by Dabović et al. [90] show political, institutional, and economic drivers to be the key factors for urban sprawl in Serbia between 1990–2000, and in that sense, the role of urban and regional land use planning is seen as enabling urban development. Decisions that initiated the processes of land cover changes were always passed by the top governing authority [91] (p. 49). Due to the fact that over the past three centuries, artificial land cover growth has proven to be very stable, the prospect for further growth of artificial cover is expected to continue at the expense of agricultural land cover [91].

Generally, land use planning is considered as a major tool to protect farmland and to limit urban sprawl [10]. Traditional land use planning tools, such as zoning regulations, help to determine the function of properties in specific locations, for industrial, residential, commercial use, and so on. Urban agriculture, and even food ordinances, are seen as appropriate for local level regulations [19], and it closely relates to land use planning and zoning at a municipal level [92]; therefore, planning instruments have to be in line with the requirements of multifunctional agriculture, such as agricultural protection areas and the designation of cultural values to urban agriculture and local food [58].

With the adoption of planning documents, the value of land often changes tenfold, and the change in value occurs on the basis of one public authority act. It has been discussed that zoning regulations may increase urbanization pressure and the land speculation in the farmlands, where land use restrictions are not so rigid [14]. The public sector does not necessarily benefit from the fact that agricultural land is changed for housing, business, and other activities that are not in the domain of public interest; however, it will nevertheless lead to an increase in land value of ten or more times. Some tools for overcoming the speculative behavior that increases land prices are offered in practice, such as various forms of monetary compensation and conservation easements [93]. Using a zoning system, development rights can be transferred from so-called "sending areas" that are less desirable for development from a public-policy perspective, to designated areas for development which are so-called "receiving areas", with proper payment to the landowners of sending areas for the sale of their properties' development rights [48]. Nonetheless, future research is still needed to address innovative planning instruments which correspond to the needs of peri-urban farmers and city dwellers [93].

Differentiation strategies in urban agriculture involve high-value local, organic, or traditional foods, including those with GIs as indications of the product's geographical origin and qualities or a reputation due to that origin [23,25]. The origin-linked quality characteristics and cultural significance was one of the main arguments of the applicant status of the Protected Geographical Indication (PGI) of the "Lea Valley cucumber" in Greater London, 2011 [24]. The importance of the GI product for the local economy and identity, stems from the complementarity (as opposed to competition) between the production of the GI item and other activities [94], the role of local public authorities in facilitating synergy, and the balance of power between producers and other local stakeholders [65], all of which are crucial factors for GI outcomes; however, the issue of land management comes first, as the production of GI foods is based on precisely defined land areas, which, therefore, need long-term protection [51]. The strategies that protect urban and peri-urban agriculture in metropolitan areas are developed in several European countries, such as the case with the Sabadell and Baix Llobregat agricultural parks near Barcelona, Spain [26], and the Agricultural Park of South Milan, Italy [27]. In Almere, the Netherlands' urban planning gave agriculture a key position in the development of a large-scale peri-urban area, by reserving (at least) 51% of the individual plots for peri-urban agriculture, and by implementing the rule of self-organization, which attracted new residents (and new farmers) [95]. On the other hand, a study that covered urban regions in Sweden, Denmark, and Belgium prove that although protected by spatial planning tools, peri-urban farmlands are not yet recognized as an urban food security strengthening factor [96].

Contrary to the previous point, there is the example of Futog. Farmers in Futog are dissatisfied with the attitude of the local administration with regard to agricultural land, especially land designated for GI production, when it comes to its conversion into construction land. More specifically, a significant part of the agricultural land of Futog "atar", including land registered for AO cabbage production, was converted into construction land, with amendments made to the General Regulation Plan of the Futog settlement [78]. As a result, farmers were faced with multiple increases in property tax in 2018. In the case of LT in Futog, according to the urban land management program [97] conducted by the administration of the city of Novi Sad, in accordance with the provisions of the Law on planning and construction [77], the market value of construction land is about 125 times higher than the price of agricultural land; however, the capitalization of the construction land's increased value (as a result of public investment in infrastructure), occurred without taxes being levied [89].

Extended nationwide, farmers' complaints were accepted by the Law on amendments to the Law on property taxes [98], in terms of the amount of tax, which, according to the law, may be returned to previous levels as a result of the regulatory decisions of local authorities. The regulatory decision encompasses the classification of undeveloped construction land in the territory into agricultural land (i.e., forest land) for the purpose of determining the property tax base if it is used exclusively for growing plants, or planting material, namely, forests (amended Art. 6a of the law); however, the decision of agricultural land conversion remained in force. Concerning the remarks of *Futog cabbage* growers about existing agricultural land in the area that is of a lesser quality, which could be used for construction instead of their own land and is instead designated for cabbage farming, the mayor simply answered—*the city must expand* [99].

The new amendments to the plan of general regulation of the Futog settlement [79] is still in the draft phase, but based on the material available to the public in the first phase of public participation, the plan covers the area outside the building zone (i.e., on the agricultural land of "atar"), where business and commercial facilities are planned. In the covered area, currently, there is no built traffic infrastructure except for agricultural roads; therefore, it concerns the new agricultural LT of Futog "atar", including the land registered for AO cabbage production, which is not planned for public purposes. Here, the question arises: is it justifiable to expand commercial activities, housing, and so on, or to maintain food security and preserve GIs?

The city is indeed expanding, but as pointed out earlier, urban agricultural land registered for the production of GI products requires increased attention and institutional protection and support. Here, the role of land use policy and planning, as well as the active cooperation between public authorities and local stakeholders, come to the forefront.

6. Conclusions

The pressure on agricultural land is a common problem worldwide, especially nowadays, when all countries need to be fully aware of food security issues. The role of urban agriculture in addressing such issues is fully recognized. The main pressure is in peri-urban areas due to urban sprawl and LT, which is also the case in Serbia, particularly within the FUAs of Belgrade and Novi Sad. In the context of food security, the basic act is to ensure land fund preservation, because without agricultural land, there is no food production; therefore, it is quite justified to maintain and protect valuable areas of agricultural land in the Novi Sad FUA, especially urban farmland registered as a geographical area for GI production in Futog, which is particularly vulnerable and requires stronger monitoring and institutional protection and support.

Since the outcome of planned (i.e., planning decisions) and unplanned LT is clearly measurable, this study provides analysis of LT by using precise UA datasets for the period 2000–2018. UA datasets provided detailed insight into LT, which is not high for the Futog settlement, as it is closer to "zero" LT; however, even though land use planning is seen as a factor that reduces LT, the case of the Futog settlement shows the opposite. It seems as though agricultural land is "given away" instead of "taken", because current planning documentation affirms new LT. If land is not designated for agricultural use, farmers could be unmotivated for long-term investment and could even stop cultivating produce. Such a scenario is only supported by a consequent increase in property taxes. Although many studies acknowledge that peri-urban agriculture has important potential for food security, urban planning in Serbia does not take into account such potential. This leads to the conclusion that current forms of land use planning are not adequate to ensure the protection of either urban agriculture or GIs. At the same time, neither adaptation strategies nor business models based on GIs in Futog are strong enough to prevent planned LT, nor can they limit the total extent of designated building zones.

Based on the key findings regarding LT issues and agricultural land loss, the following principles for land use planning solutions and recommendations have been identified: to direct LT to land that is of marginal importance for agriculture; to stop LT for economic and socio-cultural needs, except for national interests of high priority [100]; and to identify areas with high quality agricultural land (protected agricultural areas) and include them into planning documents as "zero" LT areas. It is necessary to include all protected agricultural areas, as well as areas with GIs, into binding legislation for land use planning. Adhering to previously mentioned guidelines will bring limitations to the planning process itself in terms of new LT. Supported by municipal land use planning policies, using the agricultural protection zoning ordinances, transferable development rights based on tax incentives, and minimum density value might be a tool and recommendation for both Serbian legislative and land use planning practice. Future research of these issues is fully needed, because both urban development and GI prevention in Serbia has importance, and in that sense, this research modestly contributes.

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Notes

1. Although, land take does not always coincide with urban sprawl, since it can occur outside of urban or peri-urban areas (e.g., extraction sites) [34]. Determinants of land take are various: population and income growth, increased transport accessibility, weak or inadequate planning, and subsidies encouraging land consumption and automobile use, etc. [Ibid.]
2. The status of soil sealing and land take in the EU is issued by the European Commission, the details of which can be found in the report by Prokop et al. [36].
3. The ESPON project, Sustainable Urbanization and land-use Practices in European Regions (SUPER), analyzed how much land is converted from one use to another and offered suggestions on how to influence these developments [40].
4. Windfalls and betterment (i.e., unearned increment, plus value, value capture), denote any increase in the value of land caused by planning decisions or decisions in the public interest. These are, therefore, unearned revenues that the public sector uses for purposes in the public interest [42]. For planners, ensuring the fairness of planning and avoiding the windfall and wipeout caused by zoning are two important issues.

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Territorial Prospective to Sustainability: Strategies for Future Successful of Water Resource Management on Andean Basins

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Abstract: In Latin America, water resource management in some areas is difficult when all parts of a system are not considered (including its dynamism). Therefore, it becomes necessary to prepare instruments that facilitate management using a comprehensive approach. This study aimed to develop a methodology that allows one to conduct a prospective analysis of water management over delimited territories. The Zamora Huayco basin was chosen as the study area. This work included a survey of physical-natural, socioeconomic, and political-institutional variables, as well as a system structural analysis. Also, the generation of future scenarios and the strategic and tactical orientation for the integrated management of water resources. The results show that, of the 23 variables used, 19 were classified as key system variables. Most of the variables had strong impacts on each other, but at the same time these were highly receptive to changes. The behavior of change, proposed for the different uses and land cover in the basin for 2029, was considered as the objective scenario, highlighting the gain in forest areas and shrub vegetation. The strategic plans proposed in this methodology consider the structuring and collecting information in a single repository, creating communication channels between stakeholders and decision-makers.

Keywords: integrated water resources management; territory management; future scenarios; prospective analysis; decision support system

1. Introduction

Integrated water resources management (IWRM) encourages the coordinated acquisition and handling of water resources, with the participation of diverse stakeholders, from those related to natural water storage to end users, in order to develop economic and social welfare without risking vital ecosystems sustainability [1–3]. In this approach, the foresight techniques application has gained popularity, since it considers the most probable changes of a system and established a strategic plan to achieve a desirable future, as well as precautionary measures to control this transition [1,4–6].

Water consumption has grown exponentially worldwide since the previous decade, which is linked to population growth and economic development. This has caused problems associated with competition for its use and has affected the supply ecosystems [1,7]. Until the end of the last century, water management in the world focused mainly on meeting demand [8,9]. Also, the availability of water was apparently sufficient, and it was not necessary to analyze in depth all of the aspects related to its management. However, the scenario of global water stress reached in recent times, with a supply that decreases over to a growing demand, raises the search for new management mechanisms for water governance [10] since the traditional, fragmented and sectoral approach, is no longer valid [11,12].

Latin America has large reserves of fresh water in its territory, as it concentrates 31% of the planet's sources. However, over many significant supply areas exist conflicts between stakeholders, so, water resources sustainable exploitation turns difficult, situation related to several investigators [2,13,14]. Consequently, the use of different methods and instruments that facilitate a coordinated management has increased. In particular, for water use planning, major advancements have been developed in prospective techniques through structural analysis for decision-making, such as those carried out by [1,15].

Structural analysis is a prospective method. Its objective is to determine the main influencing and dependent variables (that is, the key variables for the evolution of the system). After listing the variables, its relation is searched among each other, and the scenarios are built. These scenarios are essentially the combination of variables and its change. The most common change scenarios prepared in an academic or research context, are the negative, positive or objective, and tendential. The negative scenario is related to the worst change over the system. The positive or objective scenario is the desirable future of the system, and the tendential scenario groups together the predicted change in each variable. All of these scenarios are developed based on expert criteria [16,17].

Within territorial prospective methodology, the generation of future scenarios is reached by identifying and classifying the relationships between different variables that characterize a system. This is the central objective of the whole process since it allows synthesize a system through the definition of key variables, and with them, propose hypotheses of change. With the combination of hypotheses of change, different scenarios are built up. One must be selected as a desirable, at which time finally the strategies to achieve it can be detailed. Some application examples exist, although their use in IWRM is limited. Therefore, the current study is based on the methodology developed by [17], for territorial management modified for water resource management.

Ref. [1] conducted out a structural analysis of the water resource management system in the Nenetzingo river basin (Mexico). They identify and classify the system variables and give a strategic orientation to the management of water resources within the basin. They used the cross-impact matrix multiplication applied to classification (MICMAC) analysis, but made-up modifications to the original method. Nevertheless, the variables used did not contain actual data of the basin, neither in current nor future conditions. A total of 49 relevant variables of the system were identified, along with 22 key variables.

Analogously, ref. [15], had the objective of investigate the methodology associated with the generation of strategic scenarios within a hydrographic basin. They integrated the theories of structural analysis, actor analysis and morphological analysis oriented to water resource management, highlighting the importance of considering the social, economic, and environmental dynamics within the territory, they worked with 11 variables for structural analysis. This study was conducted in the hydrographic basin of the Ararandeua river (Brazil), which is characterized by having a high rate of conflicts over water use.

Ref. [4] applied the MICMAC method, in order to identify the structure of key variables for environmental management in La Concordia (Ecuador). Also identified the denotative variables to intervene in the system. Similarly, the authors of [18] identified key variables in the Ruta del Oro (Colombia) regional system, conducted a MICMAC analysis, and developed planning scenarios.

The watershed used as the study area, in the proposed methodology is the Zamora Huayco (ZH) river basin. This basin has many social, economic, and political particularities, which together to specific natural conditions, generate a highly complex system. Under the conditions described above, nonassertive policies could inhibit the proper management and conservation of water resources.

Special attention must be paid to developing approaches for water management among stakeholders and decision-makers. Through guiding actions that channel safeguarding hydrological services and seeking to improve the living conditions of communities located within the hydrographic basin [14,19]. The policies must be linked with the study and monitoring of natural resources as an aid to decision-making [11]. According to this perspective, it is necessary to represent a system in all its dimensions and that includes all of the variables related to an efficient water resource management through a strategic plan to achieve it. Therefore, this study aimed to develop a methodology that allows one to conduct prospective analysis of water management systems such as watersheds, based chiefly on the phases proposed by [17].

Firstly, a survey of physical-natural, socioeconomic, and political-institutional variables was carried out, along with the analysis of the relationship between them. Then, future scenarios were generated, appending landscape management and water resource management. Based on an objective scenario, possible strategic guidelines were detailed to reach it.

2. Materials and Methods

2.1. Study Area

The Zamora Huayco (ZH) basin has 3806.52 ha, and is located in the inter-Andean region of the Loja province in southern Ecuador between the geographic coordinates 4°04′03′′–3°59′42′′ S and 79°11′54′′–79°07′35′′ W (Figure 1). The elevation ranges of this basin are from 3380 to 2560 m asl, and its average slope is 0.65 m/m.

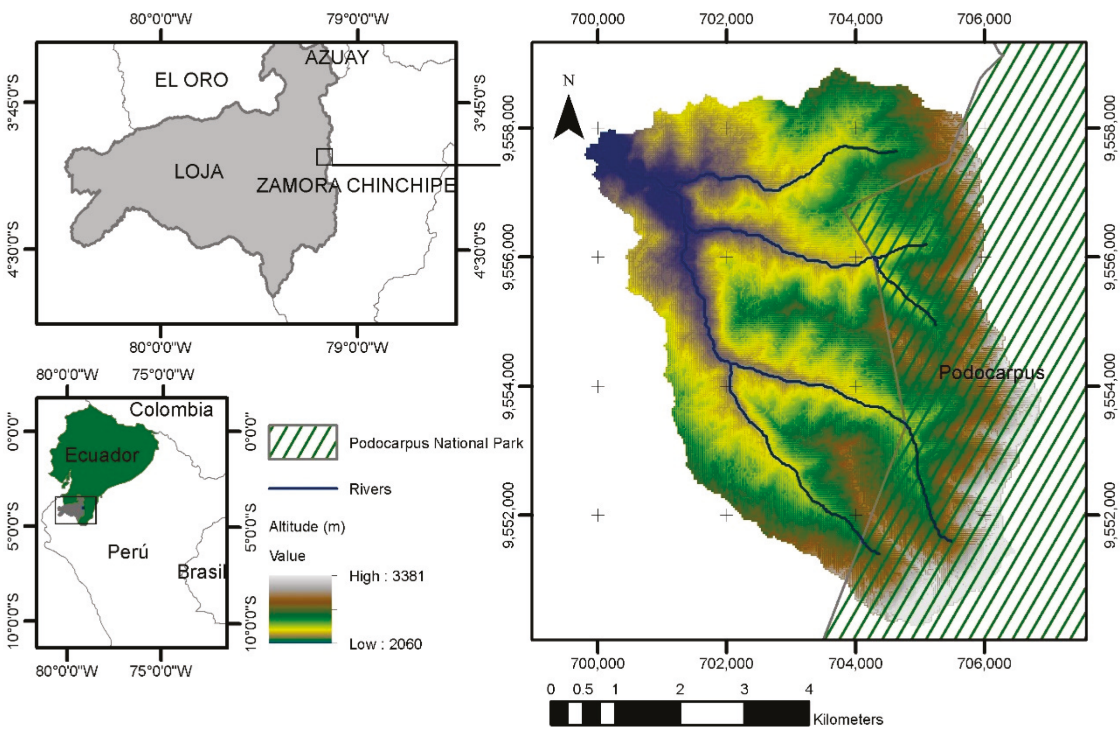

Figure 1. Location map of ZH basin.

The basin's climate is cold temperate mesothermal [20], characterized by an average annual temperature between 12 °C and 18 °C and average annual precipitation of

1047 mm. The wet season occurs from December to May and the dry season from June to November [21].

Natural vegetation predominates in the basin, although since 1976, the basin's forests have decreased by 19.3% [22]. Also, within the ZH basin, there are two water catchments for potabilization that supply approximately 50% of the demand of the city of Loja with 450 l/s [23].

The buffer zone of the Podocarpus National Park (PNP) is located in the upper zone of ZH [24]. The PNP has a strong agricultural, livestock and urban pressure in the surrounding valleys, mainly in its western limits [25], including the Loja [23]. The main productive activities in the lower zone of ZH are agriculture and cattle raising [26,27].

2.2. Prospective Analysis

In this research, a methodology for the systematic characterization of a watershed and the generation of future scenarios was developed. It is focused on the assurance of ecosystem services, to the current and futures natural conditions. To identify key variables, a cross impacts matrix was applied [28], but using a different scale than the traditional one. Also, a clustering method was applied to classify the variables and identify the key ones; this procedure is detailed in the flowchart in Figure 2.

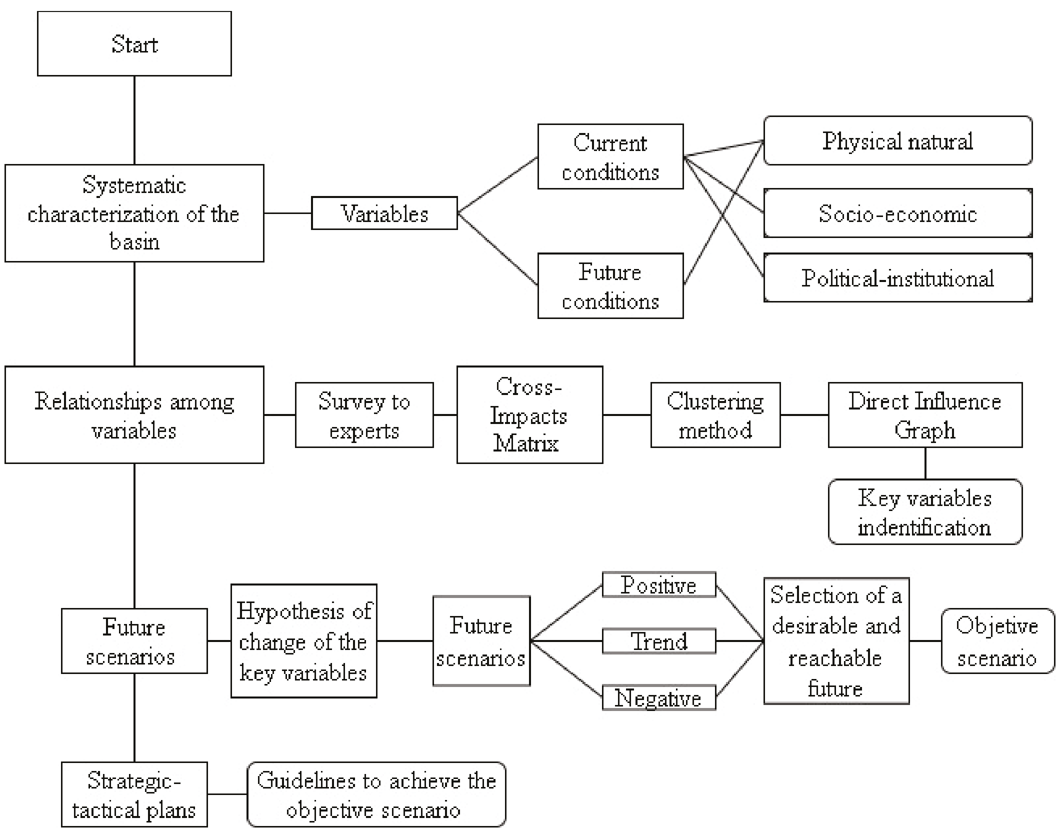

Figure 2. Flowchart showing the prospective analysis.

Different stages were generated and included considering what inputs can help us propose a decision-making system that does not depend on the subjectivity or bias of human selection; but that includes the holistic perspective of watershed management, that requires the participation of stakeholders and decision-makers, within the territorial planning of the basin.

2.2.1. Systematic Characterization of the Basin

A strategic diagnosis was included, which implied a combination of physical-natural, socio-economic, and political-institutional variables [17]. Socio-economic and political-institutional variables encompassed details under current conditions and physical-natural variables included current and projected data to a close time horizon, so that changes can be able controlled.

The natural physical variables were obtained, for current conditions and projected to a 10-year time horizon, through remote sensing techniques and hydrological modeling; for more details you can review [24]. While, the characterization of the socio-economic variables, a survey was carried out in the basin populated area, and for the political-institutional variables, an extensive bibliographic review of current regulations and laws were carried out.

2.2.2. Relationships Description among Variables and Identification of Key Variables

The analysis of relationships among variables was carried out using the DELPHI methodology [29]. A survey was prepared, and experts' participation was requested. Within this survey a brief description of identified variables was included, to handle uniformity in concepts. Also included were the objective of the consultation and procedure for completing the survey.

Experts on IWRM issues from different areas such as economic and social science, hydrology, forestry, environment, agriculture, and civil engineering were selected; from the academic, both public and private. Counting thus on the criteria of 17 experts, plus the criteria of the authors of this study. The final matrix was determined by calculating the statistical model from the matrix database [17].

The experts were asked to fill in the structural analysis matrix, or cross-impacts matrix, placing the variables in both rows and columns and evaluating the impact of each variable on the others, assigning values of 0 (no impact), 1 (slight impact), 2 (strong impact) and 3 (very strong impact). This scale was chosen since by exposing the variables to different degrees of sensitivity, it increases the possibility of having results that a priori could be counterintuitive [16,30]. A potential scale was excluded since it might highly affect the dynamism among variables, hindering the setting of an objective horizon in the near future [1], so, the most likely change was chosen. Finally, a cartesian plane was generated, called direct influence graph (DI), (abscissa and ordered correspond to horizontal and vertical summation of each variable in the structural matrix) [31].

To facilitate the selection of key variables by dividing the contiguous classes into different ranges, a data clustering method known as Jenks natural breaks (JNB) was applied, this tool has the characteristic of minimizing the squared deviation within each aggrupation [1,32]. This allowed the selection of variables that have reached a higher margin due to their higher score and eliminating variables that have obtained a lower ranking, and therefore correspond to a low influence within the watershed system.

A total of four subdivisions were considered, for a low, medium low, medium high and high level. Giving a numerical value to the classification of variables according to [16], the excluded variables are in the low, medium low and upper middle zone levels, and the key variables are distributed in the high level. In total, 23 variables and 529 influence evaluations were achieved.

2.2.3. Future Scenarios Construction

Scenarios were generated once the key variables had been obtained. The morphological space (narrative of future hypotheses or exploration of hypothesis of change) was constructed, considering an objective time horizon to the year 2029. Different hypotheses for the identified variables were described considering a positive change (desirable in the future), a trend change and a negative change. The scenarios result from the combination of hypotheses [17,33].

2.2.4. Strategic-Tactical Plans

This stage involved generating guidelines to achieve the objective scenario [17]. The guidelines were mainly oriented towards water resource conservation, flows regulation and ecosystem service assurance. Both, strategic and adaptive actions, were included due to the existence of variables that cannot be controlled, such as municipal legislation or climate change. A similar stage is placed at [34], and is highlighted as "move from prospective reflection to strategic action"

3. Results

3.1. Basin Systemic Characterization

3.1.1. Physical-Natural Domain

Physical-natural domain was extensively detailed in part 1 [24], dimensions such as LULC, water recharge estimation, flash floods, hydrological modelling, water availability and meteorological projections were quantified, and its results were associated with the narratives of future hypotheses.

3.1.2. Socioeconomic Dimension

Mostly agricultural related activities are made in the lower zone of the ZH basin [22], close to two catchwaters for potabilization [23]. While, in the upper zone, the buffer of the PNP is located, where productive or extraction activities are not allowed [27,35].

In the ZH basin, several anthropogenic problems were identified, mainly related to demographic pressure and the unequal distribution of resources and services. About 43% of the population that lives in the basin, does not have sewerage service. These are forced to use alternative sanitation solutions, such as septic tanks, cesspools, and latrines. Approximately 44% of the population is water supplied from rivers, springs, or ditches. In terms of public perception, 36% of the residents consider that the water they use at home is of poor quality. Around 36% of people have endured failure of the sewer system in their homes. Therefore, water sources are susceptible to contamination, mainly by these alternative sanitation solutions.

The survey conducted in the basin shows that 43% of the people, lived in other sectors of the city and settled in the area for work reasons. It has caused an advance of the agricultural frontier, approaching fields to areas with high slopes, increasing erosion risk and organic surface layer loss. Colonization processes, in addition to constant immigration, have caused changes of LULC and an increase in the water demand.

Low purchasing power, lack of social security (whether due to employer affiliation or peasant insurance), low level of schooling, poor employer relations, among others, have forced a large percentage of residents of ZH to develop agricultural activities that complement their income, which implies, as in previous cases, an advance of the agricultural frontier. About 48% of the population states that work more than 40 h per week, 26% work less than 40 h, and 26% do not work (mostly students, but occasionally they help with agricultural activities). People who work as salaried employees receive on an average $457 and the people who are self-employed $287. Our results do not agree with [26], 62% of the population has a productive agricultural activity, mainly related to cattle and short-cycle crops, mostly on waterways riversides. Generally, the population of the area will decrease at a rate of close to 1.56% per year [36].

3.1.3. Political-Institutional Dimension

On the upper eastern flank is the buffer zone of PNP, which maintains independent policies regarding the monitoring and protection of its territory. According to the Ministry of the Environment (MAE), it has a high conservation priority since it is part of the National System of Protected Areas (SNAP), and of the subsystem known as Heritage of Natural

Areas of the State (PANE). The SNAP has among its priorities, the preservation of biological diversity, promoting the sustainable management of wild lands, encouraging ecotourism, in addition to maintaining genetic flows [37].

SNAP is a differentiated and shared territorial administration tool, integrated by state, municipal, community and private actors (MAE, 2016). The SNAP is mainly managed with the financing of fiscal resources and subsidize from the Global Environment Facility (GEF). For 2012, $478,584 corresponding to 2.28% of the total SNAP budget, was allocated to the PNP [35].

SNAP has a budget deficit [38], accuses a lack of personnel, and maintains 95% of its lands with land tenure problems [26,35,37]. But it has achieved good results, particularly in PNP, which maintains a very good state of conservation [39]. In the ZH basin, within the area shared with the PNP, any exploitation or occupation is prohibited [35].

Also, there are conservation areas within the ZH basin, constituted as municipal domain properties, in 2007. Loja's GAD issued the following regulations: "*Ordenanza para la protección de las microcuencas y otras áreas prioritarias para la conservación del cantón Loja*", which was reformed in 2015 due to the Development and Land Use Plan update [40]. This ordinance aims to obtain economic resources to keep water sources in a state of conservation.

The non-governmental organization (NGO) Nature and Culture International (NCI), carried out projects within ZH, aimed at management and protection of protected areas. Due to the importance of their environmental services, received support from Lojas's GAD until 2009 [41]. After Loja's accession in 2009 to the Regional Water Fund (FORAGUA) mercantile trust, the assets acquired by NCI were transferred to FORAGUA [26]. The trust objective is to assure the conservation processes in the water sources, through the adequate investment of the environmental fees charged by the different municipalities. With the reform approved in 2015, the use of these resources is nowadays managed by the Municipal Drinking Water and Sewerage Unit of Loja (UMAPAL).

Land use in the basin is regulated through a zoning system, which considers the land use capacity, the current use of the land, the micro-basins that supply water for human consumption and the urban areas. The different classes of land use capacities have a weighted order and depend on variables such as the terrain slope, soil effective depth, surface texture, soil fertility, drainage, among others. ZH basin, due to its water importance and collective interest, has most of its territory classified as a conservation area [40].

According to the "Recopilación Codificada de la Legislación Municipal", article 23, there are penalty fees for negative externalities associated with contamination in watersheds due to agricultural activities, deforestation, or forest fires, main one is a coercive fine. A prohibition is established for sanitary sewer connections with discharge to streams, rivers, or their tributaries, which may generate contamination [42]. Upstream of the water catchment points, this is ratified. However, there are areas adjacent with agricultural activities.

The ZH basin has legal mechanisms that allow different actors to seek its conservation and take advantage of its ecosystem services. At the community level, according to [26], there is a limited community organization, mainly in the Parroquia *El Carmen*, on the management of resources. There is no specific territorial strategic planning for the area despite the basin hydric importance.

The "*Ordenanza para la protección de las microcuencas y otras áreas prioritarias para la conservación del cantón Loja*" proposes an environmental tax (ET), as a percentage of the unified basic salary (UBS) and the range of consumption per m^3. The use of these resources is managed by UMAPAL and must make an annual report to the city mayor, of the investment plan, indicating the destination of the funds. For example, in a range of 21 to 50 m^3 of consumption, for the residential rate, ET for each m^3 is 0.0085% of UBS and for the commercial and industrial rate it's 0.020% of UBS [43].

The agreement with FORAGUA was unilaterally terminated by the Municipality of Loja, through the reform of the ordinance, however, the mercantile trust with FORAGUA was in force until 2089 with irrevocable character. FORAGUA considered a contribution (projected) of 400,000 dollars per year [44]. However, it is unclear the intervention mechanisms or the inter-institutional strategies currently carried out between both parts.

One of the initial activities of FORAGUA was the management of funds for the property purchase that are located within zones identified as water recharge zones (WRA). FORAGUA identified about 4800 ha of WRA in the water supply basins for Loja canton. Of these zones, 1887 ha were declared as municipal reserves, and 2908 ha were purchased or managed by agreement [44].

The strategic alliances spectrum is broad for the conservation of water-supplying basins, it is developed through the environmental program "*Plan Nacional de Gestión Integrada e Integral de Recursos Hídricos*" has annexed the Municipality of Loja, Environment Ministry, National Council of Parish Governments of Ecuador (CONAGOPARE), National Secretariat of Water (SENAGUA), Provincial GAD of Loja and communities around the influence area. The objective of this alliance is to manage the water resource comprehensively to ensure the availability, sustainable use and quality of the water resource, for various human and natural uses. Some of the specific commitments of the stakeholders consist of the georeferenced identification of degraded areas and reforestation with native forest species [45].

Due to the lack of foresight from the municipality, the work scenario lacks political stability, so management at the inter-institutional level becomes complex. The canton of Loja is a complex territorial unit, it has personnel trained in public management and with the ability to design and implement adequate policies to achieve institutional objectives, as well as to guide and control local socio-territorial processes, based on the plan of the territory management currently developed [46]. The municipality of Loja permanently continuous training of its employees; of the different directions and headquarters; and through the Ecuadorian Professional Training Service [47].

3.2. System Variables

Table 1 details the system variables developed by the research team, associated with their domain field and with a short name for the DI graph.

Table 1. Domains and input variables.

Domain	Variable	Short Name
Natural-physical	LULC, extent of forest.	Bsq
	LULC, extent of shrub vegetation.	Varb
	LULC, extension of grassland.	Past
	LULC, extension of bare ground.	Sd
	LULC, extension of agriculture.	Agr
	LULC, extension of urban infrastructure.	Urb
	Extreme weather events, floods.	Ind
	Hydric recharge.	Rhi
	Climate change, increase in average temperature and extreme rainfall.	CC
	Streamflow	Cau
Socioeconomic	Agricultural activities in the basin.	Aagr
	Public entities response to extreme events.	Aex
	Population increase.	Pob
	Access routes to the basin.	AccV
	Educational infrastructure.	Infed
	Hygienic services and wastewater disposal (sewer/septic tank/latrine).	SerHig

Table 1. *Cont.*

Domain	Variable	Short Name
Political-institutional	PNP territorial management through the MAE in the upper part (eastern flank) of the basin, as part of the SNAP.	SNAP
	SNAP financing to achieve institutional objectives.	FSNAP
	Municipal domain properties, areas for the conservation of water sources	CFA
	Municipal legislation, penalty fees for negative externalities associated with the degradation of supply basins.	LMun
	Conservation of water resources through the execution of investment plans financed with ET.	FCFA
	Qualified human resources to achieve institutional objectives at municipal level.	ReHum
	Strategic institutional alliances to ensure the availability, sustainable use and quality of water resources.	AeIn

3.3. Key System Variables

The limits found with Jenks Natural Brakes (JNB) are presented in Table 2. Finally, 4 variables (low and close to low ranges) were discarded from the total of variables considered, obtaining 19 key system variables. Figure 3 shows a DI graph with influence/dependence areas according to JNB classification and by quadrants as established by [16].

Table 2. Contiguous classes limits considered and the total of variables.

Ranges	Dependence	Influence	Variables
Low	17	17	2
Close low	29	34	2
Close o high	38	47	6
High	48	59	13

When applying the JNB classification, the goodness of variance fit (GVF) was also determined, reaching a value of 0.9206, being close to 1 the adjustment of the classification is good [48].

Here, the excluded variables are those that, regardless of the quadrant in which these are found, are in the classification of low and close to low according to the JNB classification. Only those variables classified as close to high and high were considered as input, link, and resulting variables.

Most of the variables have been identified as link variables. These have strong impacts but at the same time are highly receptive to changes in the other variables. It is an interdependent dynamic of change. For example, there are variables such as the population increase that show a relative lower dependency and greater influence than the rest of variables, that means, a change in it would cause an alteration in the entire system, but it wouldn't be highly influenced by a modification in other variables, it also indicates that one of these factors of change, the most important is the anthropogenic. Forecasting future changes in it will help anticipate the effects that might cause.

There are mainly variables of high influence, and high dependence, understood as link variables, such as streamflow, which has a bidirectional effect on the current and future basin dynamics since other variables depend on its availability. It is important to strategically manage these types of variables since conflicts arise around them.

The resulting variables, such as bare ground cover, were shown to have high dependence and relative less influence, them strongly depend on the input and link variables, and their effects on the other variables are minimal.

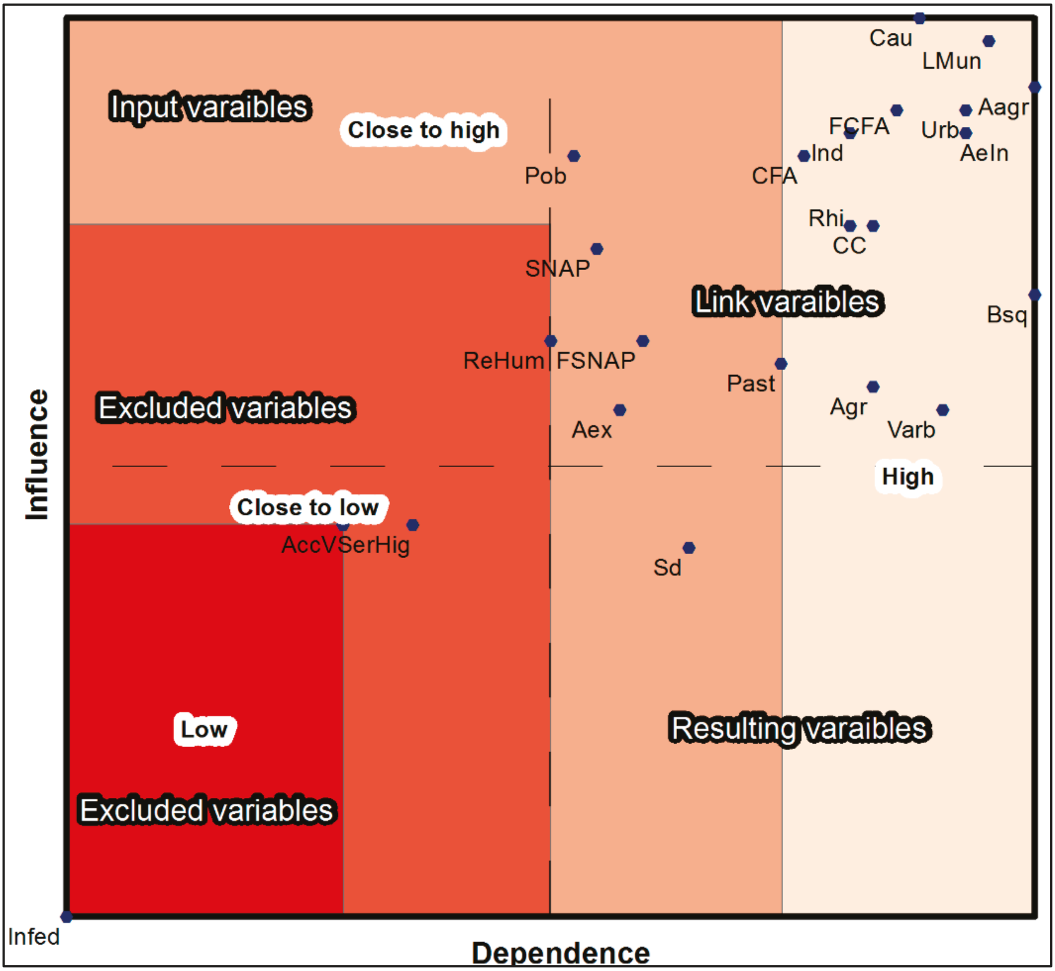

Figure 3. DI graph for ZH basin.

3.4. Future Scenarios

Tables 3–5 show the different future scenarios with a change hypothesis by variable. Strategic intervention plans must be associated with a positive scenario, as it is desirable in the future. The hypotheses of the variables of the natural physical domain were adjusted to the projections for 2029 developed in Mera-Parra et al., 2021 [24].

Table 3. Positive future change scenario, hypothesis by variable, and its characteristic.

Short Name	Change Hypothesis	Characteristic
Bsq	Forest cover will occupy more than 58.71% of the basin's extension	Link variable
Varb	Shrub vegetation cover will occupy more than 13.71% of the basin's extension	Link variable
Past	Grassland coverage will occupy less than 22.45% of the basin's extension	Link variable
Sd	Bare soil cover will occupy less than 0.45% of the basin's extension	Resulting variable
Agr	Agriculture cover will occupy less than 0.64% of the basin's extension	Link variable
Urb	Urban cover will occupy less than 4.03% of the basin's extension	Link variable
Ind	Storm-associated flow for 50 years return period will be lower than 3.00 m^3/s and the flood plain generated for a storm-associated flow for 500 years return period will be limited, on average, to 30 m from the main channel.	Link variable
Rhi	Multi-annual average water recharge will be greater than 618.45 mm, areas with the highest recharge are above 2350 masl.	Link variable
CC	An elevation greater than 0.11 °C in annual average temperature and an important increase of high intensity rainfall will present.	Link variable
Cau	A stream flow greater than 328 l/s will circulate with a 90% probability of exceedance.	Link variable
Aagr	Less than 62% of the population in the upper part of the basin will carry out agricultural activities	Link variable
Aex	Public entities response to the occurrence of extreme events will be outstanding in time and in actions.	Link variable
Pob	Population of the area will decrease at an annual rate greater than 1.56%.	Link variable
SNAP	PNP policies around monitoring and protection of the territory shared with the basin become inter-institutional, a high conservation priority is maintained, it's part of SNAP and PANE. Any exploitation or occupation is prohibited.	Link variable
FSNAP	A percentage greater than 2.28% of SNAP budget will go to PNP.	Link variable
CFA	Conservation areas will increase, constituted as municipal domain properties.	Link variable
LMun	There will be greater control and collection of fines through a coercive way to limit agricultural activities, deforestation and forest fires. Most of the territory will be assigned for conservation. There will be financial support programs for the conservation and protection of shrub and tree species.	Link variable
FCFA	ET will be adjusted according to the conditions of the different supply basins in Loja city.	Link variable
AeIn	FORAGUA will be strengthened, will administer the resources coming from ET and will obtain different lines of financing. Will implement activities oriented to the integrated management of water resources channeled to conservation, recovery and protection of environmental services.	Link variable

Table 4. Trending future change scenario, hypothesis by variable, and its characteristic.

Short Name	Change Hypothesis	Characteristic
Bsq	Forest cover will occupy 58.71% of the basin's extension	Link variable
Varb	Shrub vegetation cover will occupy 13.71% of the basin's extension	Link variable
Past	Grassland coverage will occupy 22.45% of the basin's extension	Link variable
Sd	Bare soil cover will occupy 0.45% of the basin's extension	Resulting variable
Agr	Agriculture cover will occupy 0.64% of the basin's extension	Link variable
Urb	Urban cover will occupy 4.03% of the basin's extension	Link variable
Ind	Storm-associated flow for 50 years return period will be 3.00 m^3/s and the flood plain generated for a storm-associated flow for 500 years return period will be located, on average, to 30 m from the main channel.	Link variable
Rhi	Multi-annual average water recharge will be 618.45 mm, areas with the highest recharge are above 2350 masl.	Link variable
CC	An elevation of 0.11 °C in annual average temperature and an increase of high intensity rainfall will present.	Link variable
Cau	A stream flow of 328 l/s will circulate with a 90% probability of exceedance.	Link variable
Aagr	About 62% of the population in the upper part of the basin will carry out agricultural activities	Link variable
Aex	Public entities response to the occurrence of extreme events will be appropriated in time and in actions.	Link variable
Pob	Population of the area will decrease at an annual rate of 1.56%.	Link variable
SNAP	PNP policies around monitoring and protection of the territory shared with the basin continues independent, a high conservation priority is maintained, it's part of SNAP and PANE. Any exploitation or occupation is prohibited.	Link variable
FSNAP	A percentage of 2.28% of SNAP budget will go to PNP.	Link variable
CFA	Conservation areas maintain, constituted as municipal domain properties.	Link variable
LMun	There will be fines through a coercive way to limit agricultural activities, deforestation and forest fires. Most of the territory will be assigned for conservation.	Link variable
FCFA	ET will be maintained.	Link variable
AeIn	FORAGUA will administer the resources coming from ET. Will implement activities oriented to the integrated management of water resources channeled to conservation, recovery and protection of environmental services.	Link variable

Table 5. Negative future change scenario, hypothesis by variable, and its characteristic.

Short Name	Change Hypothesis	Characteristic
Bsq	Forest cover will occupy less than 58.71% of the basin's extension	Link variable
Varb	Shrub vegetation cover will occupy less than 13.71% of the basin's extension	Link variable
Past	Grassland coverage will occupy more than 22.45% of the basin's extension	Link variable
Sd	Bare soil cover will occupy more than 0.45% of the basin's extension	Resulting variable
Agr	Agriculture cover will occupy more than 0.64% of the basin's extension	Link variable
Urb	Urban cover will occupy more than 4.03% of the basin's extension	Link variable
Ind	Storm-associated flow of a 50 years return period will be greater than 3.00 m^3/s and the flood plain generated of a storm-associated flow for 500 years return period will extend, on average, further 30 m from the main channel.	Link variable
Rhi	Multi-annual average water recharge will be lower than 618.45 mm, areas with the highest recharge are above 2350 masl.	Link variable
CC	An elevation lower than 0.11 °C in annual average temperature and a minimum increase of high intensity rainfall will present.	Link variable
Cau	A stream flow lower than 328 l/s will circulate with a 90% probability of exceedance.	Link variable
Aagr	More than 62% of the population in the upper part of the basin will carry out agricultural activities	Link variable
Aex	Public entities response to the occurrence of extreme events will be deficient in time and in actions.	Link variable
Pob	Population of the area will decrease at an annual rate lower than 1.56%.	Link variable
SNAP	PNP policies around monitoring and protection of the territory shared with the basin become inter-institutional, there is overlap of functions with other institutional instances, a high conservation priority is maintained, it's part of SNAP and PANE. Despite being prohibited, there are areas with exploitation or occupation. Control is minimum.	Link variable
FSNAP	A percentage lower than 2.28% of SNAP budget will go to PNP.	Link variable
CFA	Conservation areas will decrease, constituted as municipal domain properties.	Link variable
LMun	There will be greater control and collection of fines through a coercive way to limit agricultural activities, deforestation and forest fires. Most of the territory will be assigned for conservation. There will be financial support programs for the conservation and protection of shrub and tree species. However, due to lack of control, those aren't executed	Link variable
FCFA	ET is not applied.	Link variable
AeIn	The agreements with FORAGUA end unilaterally, the resources from ET are passed to UMAPAL.	Link variable

3.5. IWRM Strategies and Tactics

Population increase could be considered an input variable since it has a high influence and a relatively less dependency compared to the rest of the link variables. To achieve a state of conservation on water resources, efforts must be channeled to prevent population growth. Within the basin, most of the impacts on water resources have an anthropogenic origin. As the population decreases, it is expected that agricultural activities will also decrease. Ref. [49] in a study carried out in the Vilcanota-Urubamba basin, southern Peru, the importance of considering the participatory and social approach to solve anthropogenic effects and socioeconomic disparities in IWRM is highlighted.

Most of the variables, being interdependent, are conditioned to the appearance of conflicts due to the changes that are generated in them. To reach an objective horizon, forest and shrub vegetation covers, must be extended, which implies a reduction in grassland, bare soil, agriculture, and urban cover. From this viewpoint, it becomes essential, a monitoring to, if necessary, take corrective actions and procure the increased cover of forest and shrub vegetation. The collection of information requires a participatory approach with the stakeholders to integrate different elements of information through GIS. This vision is shared by [50].

It is expected that FORAGUA will retake its intervention and consequently take the competences assumed by UMAPAL. Therefore, depending on an ET (adjusted in the future according to the conditions of the different supply basins in the city of Loja), it is estimated an increase in areas intended for conservation. Similarly, the Regional Water Fund (FORASAN) in Piura, Peru, has achieved positive results in the protection of high Andean hydrographic basins following mechanisms similar to those of FORAGUA, highlighting the importance of involving stakeholders, especially the peasants [51].

Being a PNP area shared with the ZH basin, MAE must adopt actions to ensure a good conservation of associated ecosystem services. Mainly the strengthening of alliances for monitoring and protection. Dependent on SNAP, the financing lines should not be cut.

Ref. [50] shares this criterion and mentions that monitoring must include biological and chemical aspects as well as ways to transfer knowledge with decision-makers.

Control and collection of fines for negative externalities associated with the conservation of the basin must become more rigorous, to limit agricultural activities and/or deforestation, ensuring also sanction to the provocation of forest fires. While still existing private domain extensions, if these cannot be dispossessed, financial support programs must be implemented for the conservation and protection of shrub vegetation and forest. Ref. [52] mentions that, if land tenure requirements, legal restrictions, biophysical limits of land use and financial need are considered, financial support programs become attractive, not only for rural communities, if not for larger and even wealthier landowners.

These actions, in general terms, will help achieve a desired hydrological response, such as better water regulation, a lower peak flow (associated to extreme rainfall events) and a higher base flow, as well as a greater water recharge. Additionally, when observing that the areas that seek greater water recharge are above 2350 m asl, agricultural activities should be limited to this level, ref. [51] coincides in this action and adds that, to increase the resilience of the water supply, planning should focus on sources, beyond urban areas.

When evidencing a notable increase in average annual temperature and an increased tendency of high intensity rainfall, adaptive measures should be taken around climate change. Efforts should be made to protect forest areas and shrub vegetation since these are the covers that mainly regulate flow in the basin, those landscapes can help mitigate the effect of climate change on the proposed time horizon, reducing the effect of torrential floods and desertification due to hydric erosion, as long as its geographic expansion is assured.

Ref. [51] approached climate change paradigms similar to that was planned in this research, he suggests that the existing hydraulic infrastructure; designed originally to control the flow and satisfy the demand for water; will be challenged by droughts, high intensity precipitation and sediments dragged by hydric erosion, which will increase in magnitude and frequency. Therefore, those events must be estimated, the infrastructure redesigned and its conditions reestablished, if necessary, to appease the impacts. Additionally, it is essential to seek the increase of green infrastructure to mitigate the effects of climate change (floods and desertification).

To complement the holistic vision of water resource management, and given the vital importance of the basin for Loja city, it's necessary to include in the strategies, the monitoring of flow and water quality, in streamflow where water is collected for human consumption. Ref. [50] argues that technology implemented around water should not be limited to its treatment, it should be implemented in planning phases, including knowledge transfer to facilitate decision-making.

4. Discussion

At the first stage, the proposed methodology supports the need for a solid framework of natural-physical variables, in current and future conditions. Over the analysis of the relationship between variables, it is distinguished that, the 'potential' influence scale, frequently used in similar cases, was ruled out to assure a more probable objective scenario.

At the phase of the morphological space (that is, the construction of future scenarios), real and therefore controllable trends were included. This aimed to increase the probability of apparition of a more probable target scenario, and therefore, a more assertive strategic plan to achieve it. It is remarkable also that over the final evaluation of the MICMAC, the clustering method applied for the automatic selection of key variables revealed that most of the variables prepared by the researchers presented high influence and dependence, and just a few variables were ruled out from later analysis.

The proposed methodology intrinsically seeks to avoid human decision bias, which could arise due to the conditions of the interviews with stakeholders and decision-makers. As well as those that could occur due to the perceptions of the researchers.

In this study case, there are mainly variables of high influence and dependence, understood as link variables. Those have strong impacts but at the same time them are highly receptive to changes, that is, there's an interdependent dynamic of change. For example, the variable related to streamflow has a bidirectional effect on the current and future basin dynamics since other variables depend on its availability. It is important to strategically manage these types of variables since conflicts arise around them.

The resulting variables, such as bare ground cover, are shown to have high dependence and relative less influence. This strongly depends on the input and link variables, and their effects on the other variables are minimal. While the variable related to population increase has a relative lower dependency and greater influence than the rest of variables. This means that a change in it would cause an alteration in the entire system, but it would not be highly influenced by a modification of the state of any other variable and that variations in anthropogenic variables can lead to important changes and must be anticipated.

5. Conclusions

From the 23 variables considered, after the structural analysis, 4 were discarded and scenarios were generated with 19 key system variables. Most of the variables have strong impacts on each other, but at the same time these are highly receptive to changes in other variables, them are highly interdependent. This type of variable is also characterized by being associated with conflicts of interest. Therefore, an alteration in a variable must be planned and consider stakeholders and decision-makers.

The objective scenario considered the behavior of change proposed for the different land uses and covers in the basin for 2029, highlighting the gain of forest areas and shrub vegetation. Which implies a greater regulation of flow, an improvement in the protection of soil superficial layer a repowering other associated ecosystem service. A reduction in agriculture and livestock practices is also expected, mainly due to municipal intervention policies for hydric resources preservation, in addition to a negative population growth trend.

From the strategic and tactical plans, it is determined that structuring and compiling all of the information and data that may be relevant in a single GIS repository will favor decision-making. With this proposed methodology, decision-making towards the sustainable use of the water supply basins will be greatly facilitated.

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Multi-Scenario Simulation of Land-Use Change and Delineation of Urban Growth Boundaries in County Area: A Case Study of Xinxing County, Guangdong Province

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Abstract: Delineating urban growth boundaries (UGBs) by combining the land-use/land-cover (LULC) change simulation method has become common in recent studies. However, few of the existing studies have integrated multi-source big data to analyze the driving factors of LULC dynamics in the simulation. Moreover, most of previous studies mainly focused on the UGBs delineation in macroscale areas rather than small-scale areas, such as the county area. In this study, taking Xinxing County of Guangdong Province as the study area, we coupled a system dynamics (SD) model and a patch-generating land-use simulation (PLUS) model to propose a framework for the LULC change simulation and UGBs delineation in the county area. Multi-source big data such as points of interest (POIs), night-time light (NTL) data and Tencent user density (TUD) were integrated to analyze the driving forces of LULC change. The validation results indicate that the coupled model received high accuracy both in the land-use demand projection and LULC distribution simulation. The combination of multi-source big data can effectively describe the influence of human socio-economic factors on the expansion of urban land and industrial land. The UGBs delineation results have similar spatial patterns with the LULC change simulation results, which indicates that the proposed UGBs delineation method can effectively transform the LULC simulation results into available UGBs for the county area. It has been proven that the proposed framework in this study is effective for the LULC change simulation and UGBs delineation in the county area, which can provide insight on territorial spatial planning in the county area.

Keywords: urban growth boundaries (UGBs); LULC change simulation; multi-source big data; SD model; PLUS model; county area; Xinxing County

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1. Introduction

Since the Reform and Opening-Up policy in 1978, China has been undergoing intense urbanization. Urban sprawl that occurs from the fast development of the economy and population has become a huge challenge for urban planning and urban sustainable development [1,2]. Similar to other developing countries, in China, the urban sprawl is also inevitable at the expense of occupying essential ecological resources (farmland, forestland or grassland) that contributes significantly to the urban environment from development [1,3–5]. This phenomenon has become more serious due to the lack of scientific and efficient approaches for the urban planner to deal with this problem [3]. In order to manage the disorderly urban expansion, many practical works have been proposed in previous research [6–9]. Among these, the delineation of urban growth boundaries (UGBs) is suggested to be an efficient method to assist urban planners to guide the direction of urban land expansion [10–12]. The initial spatial pattern of the UGBs can be traced back to the city green belt in the 1930s, which was well-employed in the later urban planning of London [13]. Jun employed UGBs for the optimization of spatial patterns to restrain disorderly urban sprawl in Portland [14]. After that, a growing volume of research has paid more attention to the use of UGBs to assist the urban planner in constructing scientific urban land policies, to restrict future urban shapes within predefined boundaries [15–17].

Prior methods to delineate UGBs can be summarized into two major categories, including the approaches dependent on land-use/land-cover (LULC) suitability evaluation, and the approaches based on future LULC change simulation [1,18]. The former can be easily conducted by considering a series of native features (e.g., location, transportation and natural conditions) and have been largely applied in previous studies [19,20]. Nevertheless, evaluating the suitability of LULC requires a comprehensive understanding of the research area, because these factors can implicitly drive urban change at different spatial–temporal scales in a complex way [16]. Moreover, the determination of the weight of each factor in the scoring process is mainly based on the personal experience of planners, which may sometimes lead to a biased conclusion [21]. Hence, some UGBs delineation approaches based on LULC change simulation models have emerged accordingly. Among them, cellular automata (CA) models have been employed in many studies for establishing UGBs, due to the ability to simulate LULC dynamics at each cell by considering the transition rules and neighborhood effect [22,23]. Nevertheless, the "bottom-up" CA models in previous studies are incapable of capturing the macro socio-economic effect of urban growth, which is a kind of "top-down" effect [16,24]. Generally, this macro-effect is related to the future demand of different kinds of LULCs, which is an important basis for building urban planning policies for different scenarios.

To overcome this shortcoming, a series of CA models that combine the top-down quantitative estimation methods have been proposed. These CA models generally start from the prediction of land-use demand, such as ANN-CA [25], CLUE-S [26], Logistic-CA [27] and FLUS [1,16,17,28,29]. However, these models have lack the ability to analyze the contributions of each driving factor in the LULC process and fail to operate the simulation of multiple LULC patches. Recently, the newly proposed patch-generating land-use simulation (PLUS) model not only maintains the strength of self-adaptive inertia and the competition mechanism of the existing LULC change simulation models [28], but also introduces a new data mining framework [30]. In the traditional CA models, it is necessary to use two phases of data to mine the transition rules and verify the model with new data [25,27]. However, the PLUS model further developed the CA models by using the random forest (RF) algorithm to explore the contribution of each driving force to LULC conversion in two phases of data and to generate the probability of occurrences of land-use types, enabling the user to analyze the LULC change mechanism and receive higher accuracy in the applications of the LULC change simulation [31–35]. However, most previous studies only considered the conventional LULC change factors such as natural factors, transportation factors and location factors when simulating LULC change [36,37]. Although some of the studies have mentioned that human socio-economic factors are non-negligible driving forces for LULC change [38], few studies have tried to further extend this work due to the lack of data that illustrates human socio-economic factors. The emergence of multi-source big data brings new opportunities to explore the influence of human socio-economic factors to LULC change. Existing studies have confirmed that multi-source big data such as nighttime light (NTL) remote sensing data and Tencent user density (TUD) data can reflect human socio-economic activities at fine spatial resolutions [39–42]. Therefore, it is necessary to integrate such valuable data to the LULC simulation to explore the underlying driving forces of LULC change, especially the influence of human socio-economic factors.

UGBs delineation by simulating future LULC change under different scenarios has become common in current research [24,43,44]. Evaluating the influence of how different planning policies affect the future spatial patterns of urban areas, UGBs examined in different scenarios can provide the urban planner with useful information about the impacts of different development policies on urban management [16]. However, in terms of exiting studies related to UGBs delineation, most of them primarily focus on the large-scale areas, such as developed cities and provincial- or national-scale areas; few of them consider the delineation of UGBs in small-scale areas such as the county area.

In contemporary China, the county is an administrative unit between the urban and the village area, which works as a bridge to connect the development of urban and rural areas. Since the 19th Communist Party of China National Congress, the county area has played an essential role in integrating urban and rural area development. Owing to the support of government policies and the tide of industrial transfer from big cities, the county area has gradually become a potential area of urbanization [21,45]. However, due to the lack of timely scientific methods to manage urban development, the disorderly urban expansion in county areas may convert essential natural land into construction land, which may lead to irreversible ecological loss, such as the reduction of biological diversity [46], the weakening of ecological functions [47] and the instability of the ecosystem structure [48]. Hence, in order to realize the balance of development and environmental protection in county areas during urbanization, it is of great significance to delineate reasonable UGBs in advance to limit the development of unreasonable developing areas, which can effectively alleviate the increasingly acute conflict between urbanization and natural resource protection.

Therefore, we have proposed a UGBs-delineation framework for the county area by integrating multi-source big data. In this framework, we coupled the SD model, Markov model and PLUS model to simulate future LULC change of the county area. The Markov model and SD model were used to predict the land-use demand, and the PLUS model was used to simulate the LULC spatial distribution pattern. In addition, multi-source big data such as nighttime light (NTL) remote sensing images, points of interest (POIs) and Tencent user density (TUD) big data were introduced to analyze the driving factors of LULC dynamics. Eventually, based on the LULC change simulation results, the UGBs under different scenarios were delineated. The proposed framework was applied to Xinxing County of Guangdong Province. Xinxing County is one of the most rapidly developing counties in Guangdong Province and is undergoing fast urban land expansion. The goals of this study were: (1) to use multi-source big data to analyze the driving factors of LULC dynamics at the county level; (2) to construct a comprehensive simulation framework to predict the LULC dynamics of the county area from 2020 to 2035 under different developing scenarios; and (3) to delineate UGBs based on multi-scenarios to provide scientific references for the UGBs delineation of spatial–territorial planning in county areas of China.

2. Study Area and Data

2.1. Study Area

Xinxing County is located in the southeast of Yunfu City (22°22′–22°50′ N, 111°57′–112°31′ E) in the western–central area of Guangdong Province, China (Figure 1). The total area of the county is 1502.77 km^2, of which 89% is forestland and farmland and 6% is construction land, including urban land and industrial land. Xinxing County is one of the rapidly urbanizing areas in Guangdong Province, and its economy has developed rapidly over the last decades. The per capita gross domestic product (GDP) of Xinxing County grew from 27,688 to 63,868 Yuan RMB (according to the Yunfu Statistical Yearbook, 2020). The urban population grew from 76,846 to 221,905, and the urbanization level increased from 17.94% to 46.23%. According to the classification of county leading function types [49], Xinxing County is a leading agricultural county of Yunfu City. With socio-economic development, the area of urban land and industrial land of Xinxing County has expanded from 11.92 km^2 and 16.63 km^2 to 16.33 km^2 and 25.62 km^2 between 2015 and 2020, which implies an average annual expansion rate of 36.97% and 54.1%, respectively. However, the fast development of the construction land (urban land and industrial land) comes at the expense of the decreasing area of farmland and forestland by 2.78% and 1.97%, posing a threat to the sustainable development of food safety and ecological safety. Hence, delineating UGBs reasonably to control the direction of urban expansion effectively and protect natural resources are the main goal to be accomplished during the process of urbanization of Xinxing County.

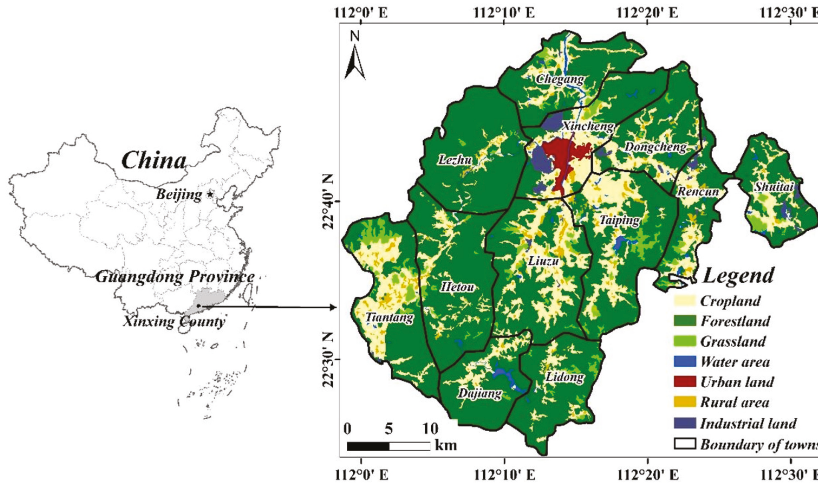

Figure 1. Location of the study area.

2.2. Data Sources and Pre-Processing

Several datasets were used in this study according to the different requirements of the models (Table 1). The data used in the SD model include land-use data and socio-economic data. The land-use data of Xinxing County for 2015 and 2020 used in this study were obtained from the Geographical Information Monitoring Cloud Platform. In this study, we reclassified the original land-use data into seven categories: farmland, forestland, grassland, water, urban land, rural area and industrial land. The socio-economic data such as population, GDP and food production were obtained from the Yunfu City Statistical Yearbook from 2015 to 2020. The land-use data used in the Markov model are the same as that used in the SD model. The PLUS model mainly requires land-use data, driving factors data and spatial restricted area data. The land-use data used in the PLUS model are the same data used in the SD and Markov models. The prime farmland protection areas and ecologically sensitive areas are the main dataset used for constructing different simulation scenarios. The former was obtained from the government of Xinxing County, and the latter was generated by the spatial analysis tool in ArcMap 10.2 [50]. As for the driving factors data (Figure 2)—other than the conventional natural, transportation and location factors—we also consider some factors that are related to human socio-economic activities by introducing multi-source big data. Previous studies have shown that nighttime light (NTL) remote sensing images have a high correlation with regional economic status [51]. Therefore, we used the NPP/VIIRS (National Polar-orbiting Partnership/Visible Infrared Imaging Radiometer Suite) data for 2019 to characterize the economic development of Xinxing County. Moreover, points of interest (POIs) of public facilities and industrial companies, acquired from the Social Big Data Platform of East China Normal University, were used to represent the densities of public facilities and industrial companies by the kernel density tool of ArcMap 10.2. Owing to the features of high spatio-temporal resolution and relevance to human activity, Tencent user density (TUD) big data has the capability to reflect the fine-grained urban population information. According to the findings of Huang et al. [39], annual TUD data can be synthesized by sampling holiday and non-holiday TUD data. In this study, we used synthesized TUD data for 2019 to characterize the population density. The spatial data involved above were processed into raster data with a resolution of 30 m using ArcMap 10.2.

Table 1. List of the data used in this study.

Category	Data	Year	Data Resource
Land use	Land use data of Xinxing County	2015	Geographical information monitoring cloud platform (http://www.dsac.cn/dataproduct/detail/200804) (accessed on 1 June 2022)
	Land use data of Xinxing County	2020	
Statistical Yearbook	GDP	2015–2020	Statistics Bureau of Yunfu (https://www.yunfu.gov.cn/yftjj/gkmlpt/mindex#679) (accessed on 1 May 2022)
	Fixed asset investment	2015–2020	
	Permanent population	2015–2020	
	Urban population	2015–2020	
	Grain production	2015–2020	
Restricted area	Prime farmland protection area	2020	Natural resources bureau of Xinxing County (http://www.xining.gov.cn/yfxxzrzy/gkmlpt/index/) (accessed on 1 May 2022)
	Ecological sensitive area	2020	Derived from spatial analysis of ArcGIS
Driving factors	Distance to railway	2020	Open Street Map (http://www.openstreetmap.org/) (accessed on 1 March 2022)
	Distance to main road	2020	
	Distance to highway	2020	
	Distance to water	2020	
	Distance to county government	2018	Baidu Map API (http://apistore.baidu.com/) (accessed on 1 March 2022)
	Distance to town government	2018	
	DEM	2020	Geospatial Data Cloud (http://www.gscloud.cn/) (accessed on 1 May 2022)
	Slope	2020	
	Aspect	2020	
	Industrial companies density	2017	Social Big Data Platform of East China Normal University (http://sdsp.ecnu.edu.cn/sdp) (accessed on 1 March 2022)
	Public facilities	2017	
	Economic development	2019	Earth Observation Group of NOAA (https://eogdata.mines.edu/products/vnl/) (accessed on 1 March 2022)
	Population density	2019	Huang et al. [39]

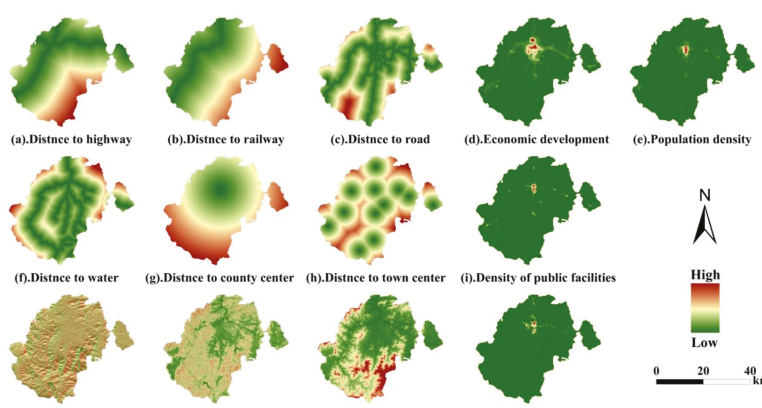

Figure 2. Spatial driving factors of LULC change simulation.

3. Methodology

In this study, we proposed the framework of UGB delineation for the county area. The framework includes: (1) land-use demand projection, (2) LULC spatial pattern simulation and (3) future UGBs delineation. The flowchart of the proposed framework is shown in Figure 3.

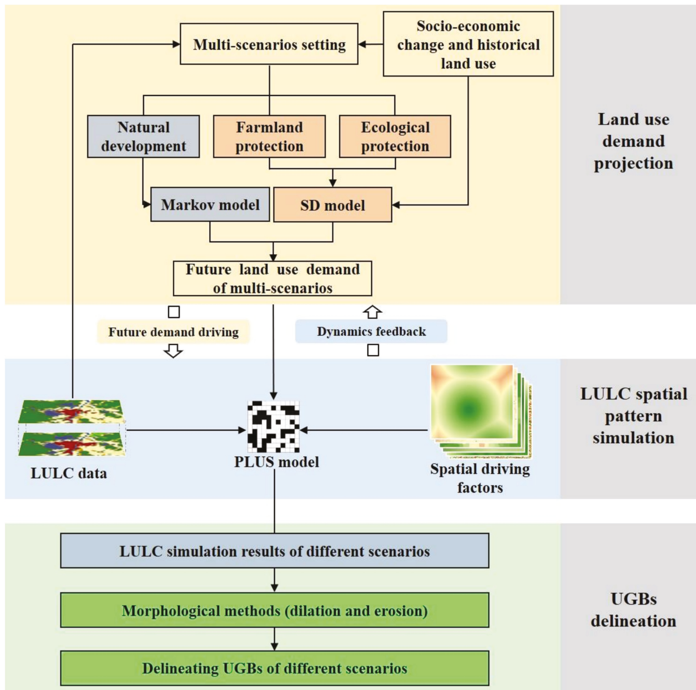

Figure 3. The flowchart of the proposed framework.

3.1. Land-Use Demand Projection

Different development scenarios will influence the direction of land-use projection. According to the scenario setting in previous studies [36,37] and specific regional LULC characteristics, we set up three different scenarios, which include a natural development (ND) scenario, farmland protection (FP) scenario and ecological protection (EP) scenario (Table 2). Since the LULC of the ND scenario is only affected by the law of historical LULC, we used the Markov chain model to predict the land-use demand of this scenario, while the land-use demand of the other two scenarios would be predicted by the SD model.

Table 2. Scenario setting.

Scenarios	Scenarios Description	Simulation Constraints
Natural development (ND)	This scenario does not consider any policy constraints on land development. The development of future demand would follow the historical law of LULC change. Therefore, the results of this scenario can be used as a reference for the simulation results of other scenarios.	No constraint.
Farmland protection (FP)	Protecting the quantity and quality of prime farmland is crucial to maintaining regional food security. Thus, it is necessary to limit land conversion in the prime farmland area to prevent the rapid loss of prime farmland owing to uncontrolled urban expansion.	Taking prime farmland protection area as the restriction and prohibiting the farmland in this area from conversion.
Ecological protection (EP)	Ecological security is essential for the maintenance of biodiversity and regional environmental quality. Hence, the protection of ecological security pattern should receive attention.	Taking the ecologically sensitive areas as restricted area where the LULC within it is unable to be converted.

3.1.1. Markov Chain Model

As for the state of the objective in the Markov chain model, its current state is only determined by the previous state [52]. In this study, the demand at $t+1$ of the ND scenario relied on the land use at t. During the prediction, the long-time series information was abandoned, and two recent periods (2015 and 2020) of land-use data were used for forecasting. The rule is as follows:

$$A_{(t+1)} = P_{(i)} \times A_{(t)} \tag{1}$$

where $A_{(t+1)}$ and $A_{(t)}$ are the amounts of land-use type k at time $t+1$ and t, and $P_{(i)}$ refers to the transfer probability matrix of land-use type k at different times.

3.1.2. SD Model

The SD model is capable of predicting both the liner and non-linear relationships between land-use demand and socio-economic factors [36]. We define seven types of land use as the horizontal variables in this model. In addition, several socio-economic factors were selected as auxiliary variables. Finally, depending on the historical law of auxiliary variables change, the future land-use demand of the FP and EP scenarios were projected by adjusting the annual growth rate of the control variables. The SD model of this study was constructed using Vensim PLE software (Figure 4)

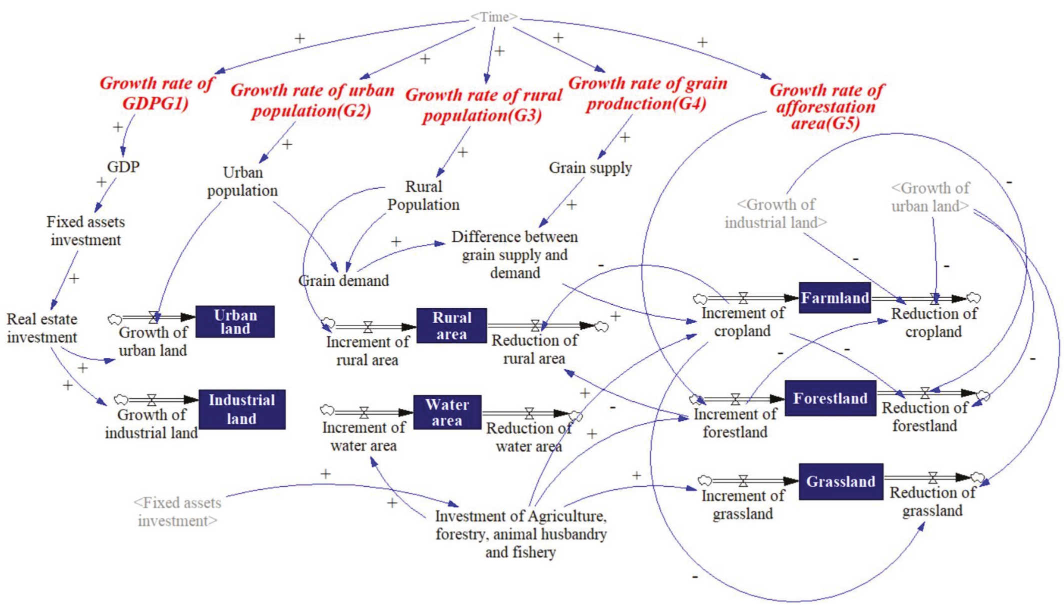

Figure 4. SD model of land-use demand projection. The symbols of + and − indicates the influence of the former to the latter, respectively positive influence and negative influence.

3.2. Future LULC Change Simulation

LULC simulation is the basis for the future UGBs delineation. In this study, we employed the PLUS model as the tool to simulate future LULC. The PLUS model includes two important modules: land expansion analysis strategy (LEAS) and a CA model based on multi-type Random Seeds (CARS) [30]. The LEAS module determines the development probability of each land-use type by using the random forest (RF) algorithm to calculate the influence of driving factors on the expansion of each land-use type. The CARS module is a CA model that integrates the impacts of macro “top-down” land- use demand and the micro "bottom-up" simulation on the land system. It incorporates an innovative multi-type random seeds generating mechanism to simulate micro-land-use competition to drive the current land-use amounts to meet the macro-demand under the comprehensive influence of self-adaptive inertia coefficient, neighborhood effect and development probability. For detailed information about the PLUS model, please refer to [30]. The overall probability $OP_{i,k}^{d=1,t}$ of the development for land-use type k is shown below.

$$OP_{i,k}^{d=1,t} = \begin{cases} P_{i,k}^{d=1} \times (r \times u_k) \times D_k^t, \ If\ \Omega_{i,k}^t = 0\ and\ r < P_{i,k}^{d=1} \\ P_{i,k}^{d=1,t} \times \Omega_{i,k}^t \times D_k^t, \qquad all\ others \end{cases} \tag{2}$$

where $P_{i,k}^{d=1}$ represents the probability of land-use type k being developed at pixel i, which can be obtained from the LEAS module; D_k^t represents the self-adaptive inertia coefficient of land-use type k, which depends on the difference between the current amount of, and future demand for, land-use type k. $\Omega_{i,k}^t$ represents the neighbourhood effect of pixel i, which is determined by the proportion of land-use of type k in the neighborhood of pixel i and the neighborhood weights. When the neighborhood effect of type k land-use is zero, the multi-type random seeds generating mechanism will generate random seeds of each land-use type through the Monte Carlo method.

Additionally, r is a random value ranging from 0 to 1, and u_k is the threshold for the generating of new land-use patches of type k. To avoid the uncontrolled growth of land-use patches, CARS integrates a decreasing threshold. If the new land-use type c wins a round of competition, a decreasing threshold τ is used to assess whether the pixel i converts to this candidate land-use type.

$$If \sum_{K=1}^{N} \left|G_c^{t-1}\right| - \sum_{K=1}^{N} \left|G_c^t\right| < Step,\ Then\ j = j + 1 \tag{3}$$

$$\begin{cases} Change, \qquad P_{i,c}^{d=1} > \tau\ and\ TM_{k,c} = 1 \\ Not\ Change, \quad P_{i,c}^{d=1} < \tau\ and\ TM_{k,c} = 1 \end{cases} \tag{4}$$

where $\left|G_c^{t-1}\right|$ and $\left|G_c^t\right|$, respectively, denote the difference of land-use amount between the $(t-1)$th iteration and future demand and (t)th iteration and future demand. $Step$ is the step size required to approximate future land-use demand; δ is the decay factor of the decreasing threshold τ, with a value range of 0 to 1; r is a normally distributed stochastic value with a mean value of 1, which ranges from 0 to 2; j represents the decay step size. $TM_{k,c}$ is conversion matrix that decides whether land-use type k can convert to land-use type c. In the CA model, the pixels with higher overall potential are more likely to convert, but after integrating the decreasing threshold mechanism in the CA model, it allows the random land-use patches to grow freely and spontaneously under the restriction of growth probabilities, which improves the accuracy of multi-type land-use simulation.

3.3. Delineating UGBs by Morphological Method

Generally, some small and scattered construction land patches with low compactness are not suitable to designating UGBs. Hence, in this study, two morphology operators, including dilation and erosion, were used to eliminate these small patches and produce UGBs by opening and closing operation. In the open operation, the dilation step will be operated first to keep most of the boundary pixels without noise. Then, the erosion step will eliminate the isolated patches [16]. The opening operation can be shown as below:

$$X \circ B = (X \oplus B) \ominus B \tag{5}$$

In contrast, the close operation is a dilation step followed by an erosion step, which can be expressed as below:

$$X \cdot B = (X \ominus B) \oplus B \tag{6}$$

The opening and closing operations are usually applied for edge smoothing and internal filling on areas for images based on the morphological way. In this study, both of the two operations were used to process the simulated construction land patches (urban land and industrial land) to generate available UGBs.

4. Results

4.1. Model Validation

Only when the models used were validated could their results be considered credible. In this paper, the SD model and PLUS model were employed to the land-use demand prediction and land-use spatial simulation, respectively. The relative error index and kappa coefficient were used to validate the results, respectively. According to Table 3, the differences between the simulated results and the actual land-use demand are relatively small: the average value of relative error is 1.3%, and the highest value is less than 4%. When the value of error is less than 6%, it means a high accuracy of the model [26]. Additionally, the comparison between the actual land-use data and the simulated result generated by the PLUS model are shown in Figure 5. It is easy to find that there is lots of similarity in the spatial pattern between the simulated result and the actual data. The kappa coefficient is 0.92, and the overall accuracy is 96.03%. Generally, when kappa > 0.75%, it indicates good consistency of the simulation. Based on this fact, the closer the kappa value is to 1, the higher the accuracy of the simulation. Hence, both models received relatively high accuracy in the validation, which indicates that they could be applied to future LULC change simulations.

Table 3. Comparison between projected areas and actual areas of 2020 (km^2).

	Farmland	Forestland	Grass Land	Water Area	Urban Land	Rural Area	Industrial Land
Actual area	329.78	1003.64	55.62	24.29	16.33	47.49	25.62
Simulated area	330.75	1004.89	55.21	23.48	15.77	46.15	25.98
Relative error	0.3%	0.12%	0.74%	3.36%	3.43%	1.38%	0.04%

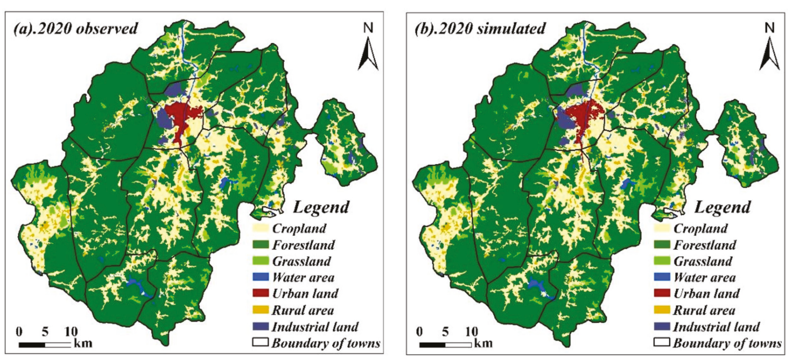

Figure 5. The comparison between the simulated LULC and the observed LULC in 2020.

4.2. Analyzing the Underlying Driving Forces of the LULC Change

By adopting the LEAS module of the PLUS model, it is more convenient to analyze the driving factors for LULC change. As mentioned in Section 2.1, the urban land and industrial land of Xinxing County has undergone evident expansion from 2015 to 2020, which has led to a lot of farmland and forestland being encroached upon. Here, we selected natural factors, transportation factors, location factors as well as human socio-economics factors to analyze the underlying driving forces of the expansion of urban land and industrial land in Xinxing County from 2015 to 2020. Figure 6 presents the variable importance that illustrates the contribution of each driving factor to the growth of urban land and industrial land. Figure 7 shows the LULC of 2015 and 2020. Two sub-regions with evident LULC change were selected to reveal the dynamic change of these two land types, in which subregion 1 is the central part of Xincheng Town where the government of Xinxing County is located, and subregion 2 is the main location where most of ceramic industries of Xinxing County are located, including Rencun Town and Shuitai Town. From Figure 6, it is obvious that the distance to the county government has the most significant contribution to the growth of urban land, and economic development also plays an important role in influencing the expansion of urban land. From the perspective of spatial location, we found in subregion 1 of Figure 7 that the new-growth urban land was mainly distributed around the central region of Xinxing County. Thus, it can be inferred that the urban land of Xinxing County is more likely to expand to the regions close to the county government with a well-developed economy. In terms of the expansion of industrial land, its expansion is mostly influenced by natural conditions, such as elevation and the proximity to water. Except for these two significant factors, human socio-economic factors such as the density of population and industrial companies also have evident contribution to the growth of industrial land. It is easy to discover from subregion 1 and subregion 2 that the new-growth industrial land is mainly located in the areas with low elevation and short distance to water, as well as dense population and industrial companies. This suggested that the combination of multi-source big data can effectively reveal the influence of human socio-economics factors on the growth of urban land and industrial land.

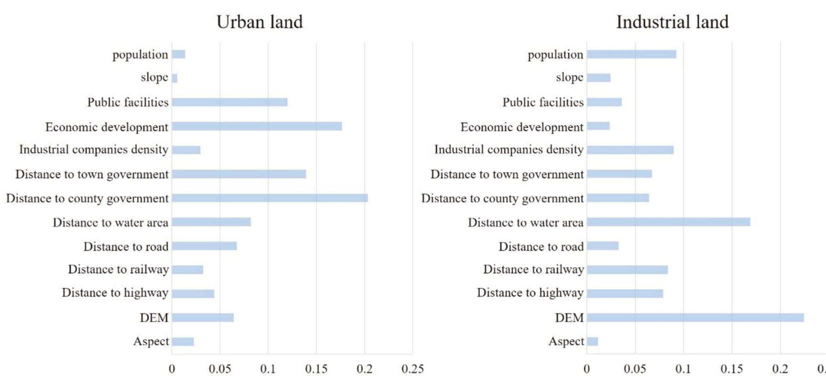

Figure 6. The contribution of each driving factor to the growth of urban land and industrial land.

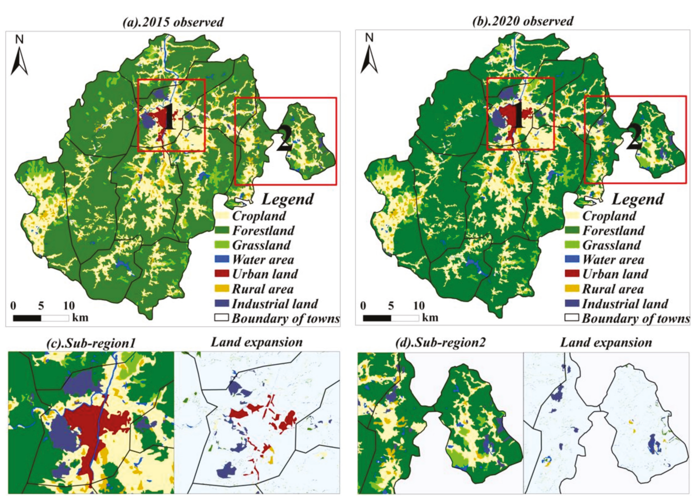

Figure 7. The LULC change map of 2015–2020.

4.3. Multi-Scenario LULC Simulation

For future LULC simulation, firstly, we predict the future land-use demand of different scenarios of Xinxing County in 2035 by the Markov chain model and SD model; then, the PLUS model was used to allocate the projected land-use demand to simulate the LULC change at different scenarios to support the territorial–spatial planning in Xinxing County.

4.4. Multi-Scenario LULC Simulation

4.4.1. Future LULC Demand Projection

The projection results of land-use demand under different scenarios are shown in Table 4. We found that both the FP scenario and EP scenario have the same area of water (24.76 km^2), urban land (23.72 km^2) and industrial land (29.84 km^2); the area of farmland (326.16 km^2) and forestland (1004.89 km^2) would be the maximum, respectively, in these two scenarios. In addition, although the ND scenario has the largest areas of urban land (27.52 km^2) and industrial land (46.06 km^2), it is worth noting that this scenario will lose the most farmland and forestland, which demonstrates that more attention should be paid to protect the farmland under the current trend of LULC change.

Table 4. Land-use demand projection of 2035 under different scenarios (km^2).

Type		Markov	System Dynamics	
		ND Scenario	FP Scenario	EP Scenario
	2020	2035	2035	2035
Farmland	329.79	307.36	326.16	320.01
Forestland	1003.64	991.57	999.26	1004.89
Grassland	55.62	57.09	53.52	54.41
Water area	24.29	25.08	24.76	24.76
Urban land	16.33	27.52	23.72	23.72
Rural area	47.49	48.1	45.52	45.15
Industrial land	25.62	46.06	29.84	29.84

4.4.2. Future LULC Distribution Simulation

The results of the LULC change simulation under different scenarios are shown in Figure 8. Under the ND scenario, the major features of LULC change were the rapid expansion of urban land and industrial land, and reduction of farmland and forestland, in which prime farmland areas and ecologically sensitive areas will be reduced by 1.73% and 2.51%. However, this phenomenon alleviates in the FP and EP scenarios due to the spatial restricted areas. In subregion 1 of the ND scenario (Figure 8b1), it is obvious that the new-growth patches of urban land and industrial land will expand and occupy a large portion of surrounding farmland and forestland. In the EP scenario, due to the restriction of the ecologically sensitive area, the distribution pattern of the industrial land in subregion 1 (Figure 8c1) remained almost the same as in 2020. At the same time, due to the EP scenario, which had the highest demand for forestland, some small patches of forestland appear in the north of subregion 1. In contrast to the EP scenario, some new patches of industrial land were generated in the left of subregion 1 of the FP scenario (Figure 8d1), but the area of these patches is less than that of the ND scenario. In subregion 2, the simulation result of the ND scenario (Figure 8b2) presents the most significant increase of industrial land along with the existing industrial land, as well as a small portion of farmland converted into rural area and water area at the south of this region. Under the EP (Figure 8c2) and FP (Figure 8d2) scenarios, the growth of industrial land was restricted to reduce the decrease of farmland and forestland. Furthermore, under the EP scenario, some patches of grassland and forestland were predicted to appear in subregion 2.

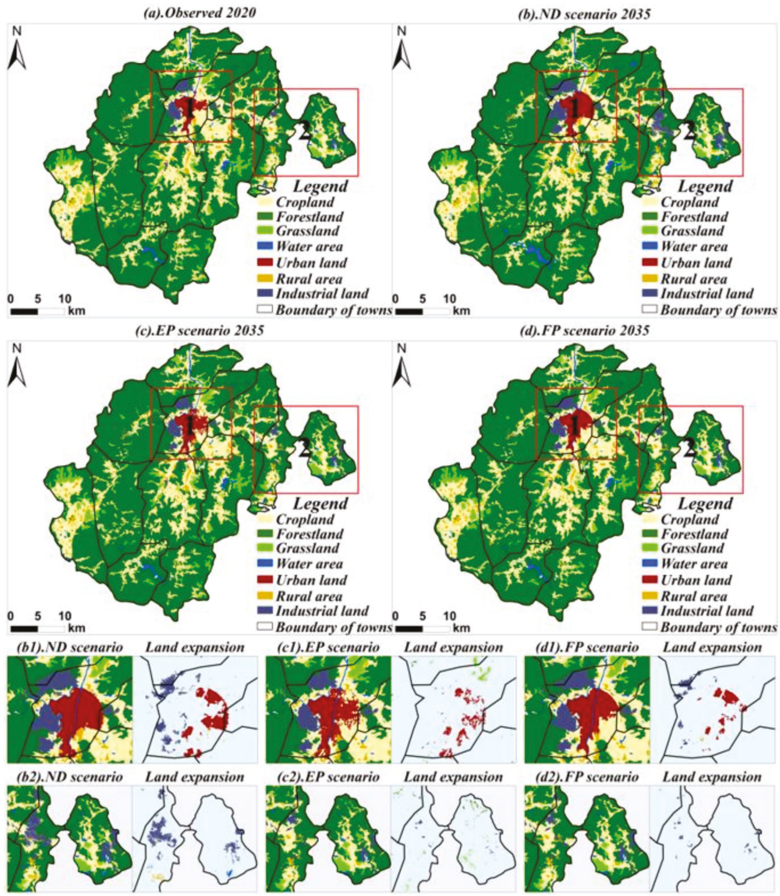

Figure 8. Simulated LULC patterns in 2035 and land expansion maps from 2020 to 2035 under different scenarios.

4.4.3. UGBs Delineation

The simulated LULC distribution results obtained from the PLUS model are fragmented and discrete, and the manual identification of the UGBs in this case is prone to misjudgment. Morphological methods, including dilation and erosion algorithms, were used to produce the UGBs based on the simulated LULC results. Then, the raster-formatted UGBs were converted into vector-formatted UGBs by GIS software, and some small patches with an area of less than 3 km^2 were removed.

The UGBs delineation results of the ND, EP and FP scenarios are presented in Figure 9a1, 9b1 and 9c1, with an area of 78.7 km^2, 51.76 km^2 and 54.31 km^2, and a growth rate of 87.6%, 23.38% and 29.48%, respectively.

In subregion 1, under the history law, the UGBs delineation result of the ND scenario has the biggest scope, and the edge of the UGBs is the smoothest among the UGBs of other scenarios. In the west of the Xincheng Town, since the restriction of ecologically sensitive area, there is little expansion of construction land in the EP scenario (Figure 9b2); instead, there is evident conversion of forestland to construction land in the ND (Figure 9a2) and FP scenarios (Figure 9c2). At the same time, due to the constraints of the ecological area and prime farmland protection area, the edges of UGBs result in the EP and FP scenarios are more irregular than that of the ND scenario.

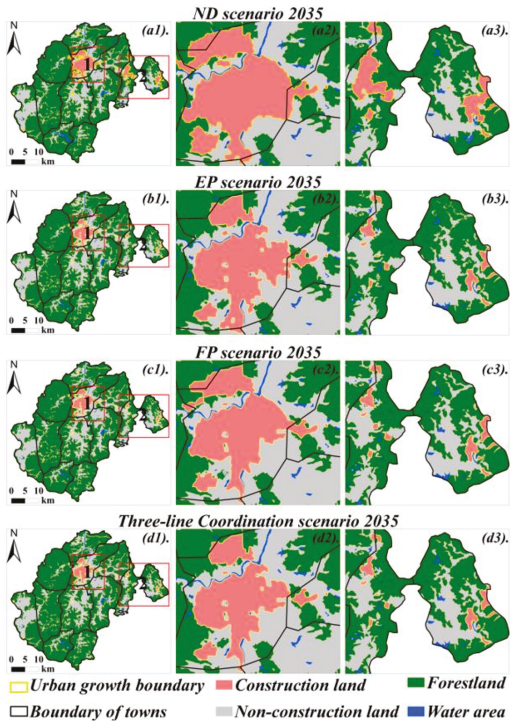

Figure 9. UGBs delineation results of Xinxing County in 2035 under different scenarios. The a2, b2, c2, d2 show the UGBs delineation of sub-region1, the a3, b3, c3, d3 show the UGBs delineation of sub-region2.

In subregion 2, the scope of the UGBs of the ND scenario is 21.25 km^2 (Figure 9a3), which is obviously bigger than the UGBs scope of the EP scenario (8.79 km^2) (Figure 9b3) and FP scenario (7.53 km^2) (Figure 9c3); however, the evident expansion in this scenario would lead to a big portion of forestland and farmland being encroached upon. In addition, the UGBs results in the EP and FP scenarios have a very similar spatial pattern and scope under the constraints of the ecologically sensitive area and prime farmland protection line. From the UGBs delineation results of the multi-scenario above, it is easy to find that these UGBs delineation results retain the same spatial distribution characteristics of the simulated LULC patterns under different scenarios, which indicates that the UGBs delineation method can effectively transform the LULC change simulation results into available UGBs for the county area.

5. Discussion

5.1. Delineating UGBs with and without "Three-Line Coordination"

In the LULC change simulation, the goals of setting the simulation scenarios of EP and FP were to prevent ecologically sensitive areas and prime farmland resources from encroachment during urbanization. These goals can be achieved at the same time by following the rule of "Three-line Coordination" when delineating UGBs. The concept of "Three-line" refers to the prime farmland protection line, ecological red line and UGBs [53]. In the new Chinese territorial–spatial-planning system, the "Three-line Coordination" is an essential standard to measure the relationship between urban development and the protection of agricultural land and ecological resources, which is necessary for promoting sustainable development. In the practical work of UGBs delineation, the realization of the UGBs delineation under the "Three-line Coordination" scenario can be the intersection area of the UGBs delineation results between the EP scenario and FP scenario, which indicates that this intersection area can be developed without encroaching on prime farmland and ecologically sensitive areas. This can help the urban planner to deal with the contradiction between urban development and the protection of primary farmland and ecological land use.

The UGBs delineation result of the "Three-line Coordination" scenario is shown in Figure 9d1: the area of the UGB is 48.93 km^2, with an increase of 16.63% compared with 2020. In terms of the LULC conversion, some of the forestland and farmland that is not included in the restriction area would be converted into new construction land. Compared with the UGBs delineation results of other scenarios, although the UGBs delineation result of the ND scenario presents the biggest developing area in the future, without the spatial restriction, however, a large portion of prime farmland and ecologically sensitive area would be encroached upon. In addition, in the EP and FP scenarios, due to the constraints of the ecologically sensitive area and prime farmland protection area, the development of UGBs in these scenarios can effectively prevent their occupation. However, it is still inadequate to solve the conflict between urban development and natural resource protection by employing any single constraint. This indicates that the "Three-line Coordination" scenario can help to realize the development of construction land while protecting the prime farmland area and ecological area, which is meaningful to supplement the UGBs delineation on territorial–spatial planning.

5.2. Urban Planning Suggestion

"Three-line Coordination" explains the relationship between urban development and natural resource protection, which can guide Chinese territorial–spatial planning in a more scientific and valid direction. However, in terms of the urban development of Xinxing County, there still exist some shortcomings that need to be solved. Owing to the long-established urban–rural dualistic structure in China, there is a general emphasis on the urban area rather than the rural area during the urbanization of the county area [45], which leads to the imbalance of development between urban and rural areas. According to the LULC change simulation results, an evident imbalance phenomenon exists in the development of urban land in Xinxing County, where new-growth urban land mainly appears around the central region of Xinxing County, while few appears at other towns. Xinxing County has rich tourism resources in other towns, such as Liuzu Town and Taiping Town, whose major regions are not included in the prime farmland protection area and ecologically sensitive area. However, it would be difficult to exploit such valuable tourism resources in these towns if the current development trend of Xinxing County continues. Based on the analysis result in Section 4.3, factors such as administrative location and economic development are vital in determining the expansion of urban land. In addition, the distribution of public facilities also has an important contribution to the expansion of urban land in Xinxing County. Hence, in the future, the development of public facilities should be strengthened in Xinxing County, especially the development of transportation service facilities, which can fully take advantage of the rich tourism resources, so as to further promote the development of Xinxing County.

5.3. Limitations and Future Research Prospects

Despite the merits of this study, we have to acknowledge some limitations which need to be addressed in future research. First, in terms of a future LULC change simulation, revealing the driving mechanism of each land-use type can help to understand the law of LULC change. However, only the land-use types with expansion were considered in this study, such as urban land and industrial land, while other land-use types with decrease were not considered—for example, farmland, forestland, grassland, water areas and rural areas. Hence, in future studies, it is necessary to explore the driving mechanism of each land-use type more comprehensively in the LULC change simulation, to further explore the law of LULC change. Second, policy direction plays an important role in the LULC change in the county area. However, due to the lack of relevant planning materials, the driving factors selected in this study may be imperfect to reveal the driving mechanism of each land-use type. In addition, the lack of relevant planning materials would also lead to the incomplete verification of the UGBs delineation result in this study, which can only verify the UGBs delineation result from the spatial perspective. Thus, it is expected that the effectiveness of the proposed UGBs delineation method can be further verified from the perspective of amount control by integrating more planning documents. Third, due to the lack of ecological red line protection data, we used the existing spatial datasets, such as DEM and NDVI (normalized difference vegetation index), to evaluate the ecologically sensitive area of the research area [50]. Therefore, relevant spatial data about ecological red line protection should be adopted in future.

6. Conclusions

Currently, the contradiction between people and land urban sprawl has become more and more serious due to the rapid urban sprawl. Delineating UGBs by simulating a future multi-scenario LULC is effective for serving urban planning and to deal with the existing conflict between urban development and natural resource protection. However, few of the previous LULC change simulation studies have tried to integrate multi-source big data to explore the driving factors of LULC dynamics during the simulation. In addition, most of the existing UGBs delineation studies mainly focused on the macro-scale area, and few of them have paid attention to the UGBs delineation in the county area. Hence, this study proposed a framework for the UGBs delineation in the county area. In this framework, the SD model and PLUS model were coupled to simulate a future multi-scenario LULC, and several multi-source big data that can related to human socio-economic characteristics in the micro-scale were introduced to explore the contribution of the driving factors to LULC dynamics. Finally, the morphology methods, including dilation and erosion algorithms, were employed to generate the UGBs of different scenarios based on the simulated LULC results. The proposed framework was applied to the UGBs delineation in Xinxing County, a rapidly urbanizing county area in Guangdong Province. The validation of the LULC change simulation result indicates that the coupled SD and PLUS model can accurately simulate LULC dynamics in the county area. After analyzing the driving factors of LULC dynamics, we can infer that the administrative location and human socio-economic factors, such as economic development and public facilities, are vital for the expansion of urban land. In terms of the expansion of industrial land, in addition to the important influence of environmental factors (DEM and distance to water), the density of population and industrial companies also have an evident contribution. Hence, we can conclude that the introduction of the multi-source big data can effectively reveal the influence of human socio-economic factors to the growth of urban land and industrial land.

In the 2035 LULC change simulation results of different scenarios, the main characteristics of LULC dynamics in the ND scenario was the rapid expansion of urban land and industrial land, which leads to evident encroachment on farmland and forestland. In the EP and FP scenarios, this phenomenon would alleviate due to the spatial restricted areas. At the same time, the UGBs delineation results have similar spatial patterns with the LULC change simulation results, which further proves the efficiency of the proposed UGBs delineation framework in county area.

Comparing the UGBs delineation results of the "Three-line Coordination" scenario with the ND, EP and FP scenarios, the UGBs result in the ND scenario has the biggest scope, but a large portion of prime farmland and ecological resources would be encroached upon during the expansion of construction land. Moreover, in either the EP or FP scenarios, it is still not enough to deal with the conflict between urban development and natural resource protection by employing any single constraint during future UGBs delineation. Instead, the UGBs delineation result under the "Three-line Coordination" can effectively deal with the conflict between construction land expansion and natural resource protection, which is meaningful to supplement the UGBs delineation on territorial–spatial planning.

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