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Article

Examining Spatiotemporal Urbanization Patterns in Kathmandu Valley, Nepal: Remote Sensing and Spatial Metrics Approaches

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Abstract: This paper examines the spatiotemporal pattern of urbanization in Kathmandu Valley using remote sensing and spatial metrics techniques. The study is based on 33-years of time series data compiled from satellite images. Along with new developments within the city fringes and rural villages in the valley, shifts in the natural environment and newly developed socioeconomic strains between residents are emerging. A highly dynamic spatial pattern of urbanization is observed in the valley. Urban built-up areas had a slow trend of growth in the 1960s and 1970s but have grown rapidly since the 1980s. The urbanization process has developed fragmented and heterogeneous land use combinations in the valley. However, the refill type of development process in the city core and immediate fringe areas has shown a decreasing trend in the neighborhood distances between land use patches, and an increasing trend towards physical connectedness, which indicates a higher probability of homogenous landscape development in the upcoming decades.

Keywords: land use change; spatial metrics; urban remote sensing; urbanization spatial pattern; urban mapping; LULC; Nepal

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1. Introduction

Urbanization has become a major trend worldwide in recent years. In 1920, the urban population made up 14% of the World, and reached 25% in 1950 [1]. Currently, 50% (3.3 billion) of the World population lives in urban areas [2]. Rapid urbanization is an ongoing dynamic process, and is the most dominant phenomenon in all developing countries [3]. In the 1990s, the rate of urbanization in Nepal (6.6% per annum) was among the highest in the Asia Pacific Region, higher than in Sri Lanka (2.2%), India (2.9%), Pakistan (4.4%), Bangladesh (5.3%), and Cambodia (6.2%) [4]. As the result of population growth and migration from rural to urban areas, urbanization has been recognized as a critical socioeconomic process in metropolitan areas of Nepal [4-6].

Socioeconomic processes such as migration, urban sprawl, agriculture, and forest patterns also often contribute to landscape changes. As a city grows, the increasing concentration of population and economic activities demands that more land be developed for public infrastructure (roads, water facilities, and utilities), housing, and industrial and commercial uses. Therefore, the urbanization can be considered as the observable transformation of the spatial pattern of land use and land cover, such as the transformation of agricultural and forest land uses into built-up area or the gradual transformation of rural landscape into urban forms. The transformation of rural landscape to urban landscape has caused various impacts on ecosystem structure, function, and dynamics [7,8]. Persistent dynamic land use change processes are expected to accelerate in the next several decades. Worsening conditions of crowding, housing shortages, insufficient infrastructure, and increasing urban climatological and ecological problems require consistent monitoring of urban regions [9].

However, monitoring of land use changes is needed to understand and predict the dynamic process of land use patterns at different times. This was traditionally limited due to labor intensive fieldwork that is often unable to reveal the spatial pattern of landscape changes and environmental consequences that occurred in a given time period. Significant technological advancement in data acquisition and analysis techniques in recent years has made it easier to analyze the spatiotemporal dynamics of landscape changes [10,11]. Remotely sensed images from airborne and satellite sensors provide a large amount of cost-effective, multi-spectral, and multi-temporal data to monitor landscape processes and estimate biophysical characteristics of land surfaces [9,10,12,13].

Remote sensing has long been used to map urban growth and urban morphology, and implies the mapping of the form, land uses, and density of urban areas, each having an associated shape, configuration, structure, pattern, and organization of land use [9,14,15]. Satellite imagery has the unique ability to provide synoptic views of large areas at a given time, which are not possible using conventional survey methods. A wide range of urban remote sensing applications from both sensors (active and passive) is currently available. These include quantifying urban growth and land use dynamics [1,10], landscape pattern analysis [11,16,17], urbanization [8], socioeconomic applications [18], life quality improvement [19], urban infrastructure characterization [7], microclimate and hydrology [20], and topographic mapping [21].

Kathmandu, a bowl shaped valley, which is the most populous metropolitan region in Nepal, is an interesting case to study as it imposes topographic constraints for horizontal urban expansion but faces rapid urbanization (Figure 1), having an annual urban population growth rate of 5.2% [5]. It is the main political and administrative center, a major tourist gateway, and an economically strategic location in the country. High population growth, dramatic land use changes, and socioeconomic transformations have brought the paradox of rapid urbanization and environmental consequences to the valley [3]. Along with new developments within the city fringes and rural villages, shifts in the natural environment and newly developed socioeconomic strains between residents are emerging. Such rapid demographic and environmental changes and weak land use planning practices in the past decades have resulted in environmental deterioration, haphazard landscape development (Figure 2), and stress on the ecosystem structure [22]. Consequently, more and more agricultural lands and forest lands have been converted into urban areas and human settlements over the past few decades [3]. Therefore, quantifying land use patterns and analyzing the changes over time are essential for monitoring the urbanization and environmental consequences in the valley. The main objective of this article is to examine the spatiotemporal pattern of urbanization in the valley using remote sensing and spatial metrics techniques. This is possible due to advancement of remote sensing techniques and multi-temporal satellite data availability while no other data are available for the study.

Figure 1. Urban population in Kathmandu Valley (Data source: http://www.cbs.gov.np/).

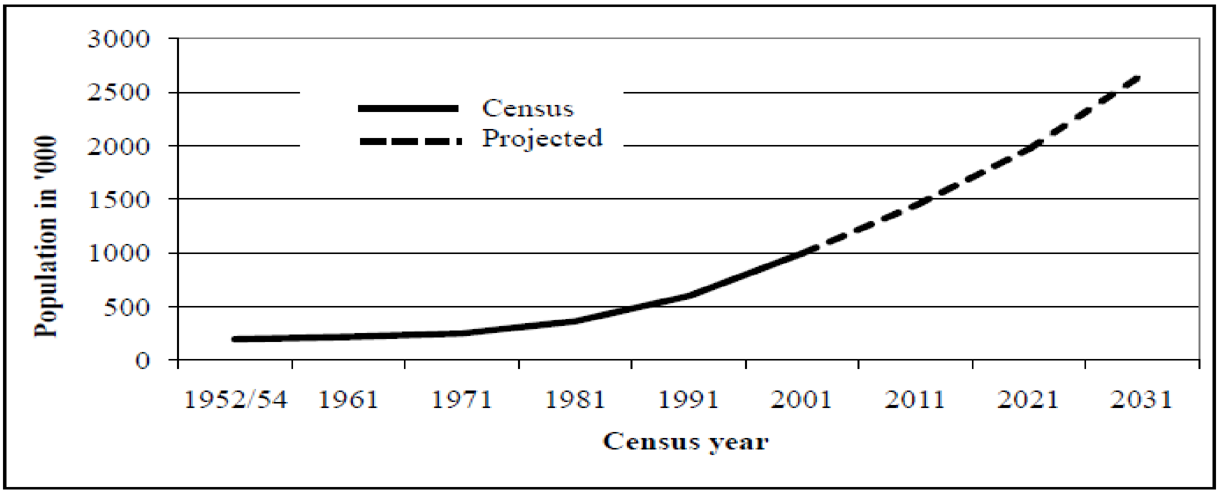


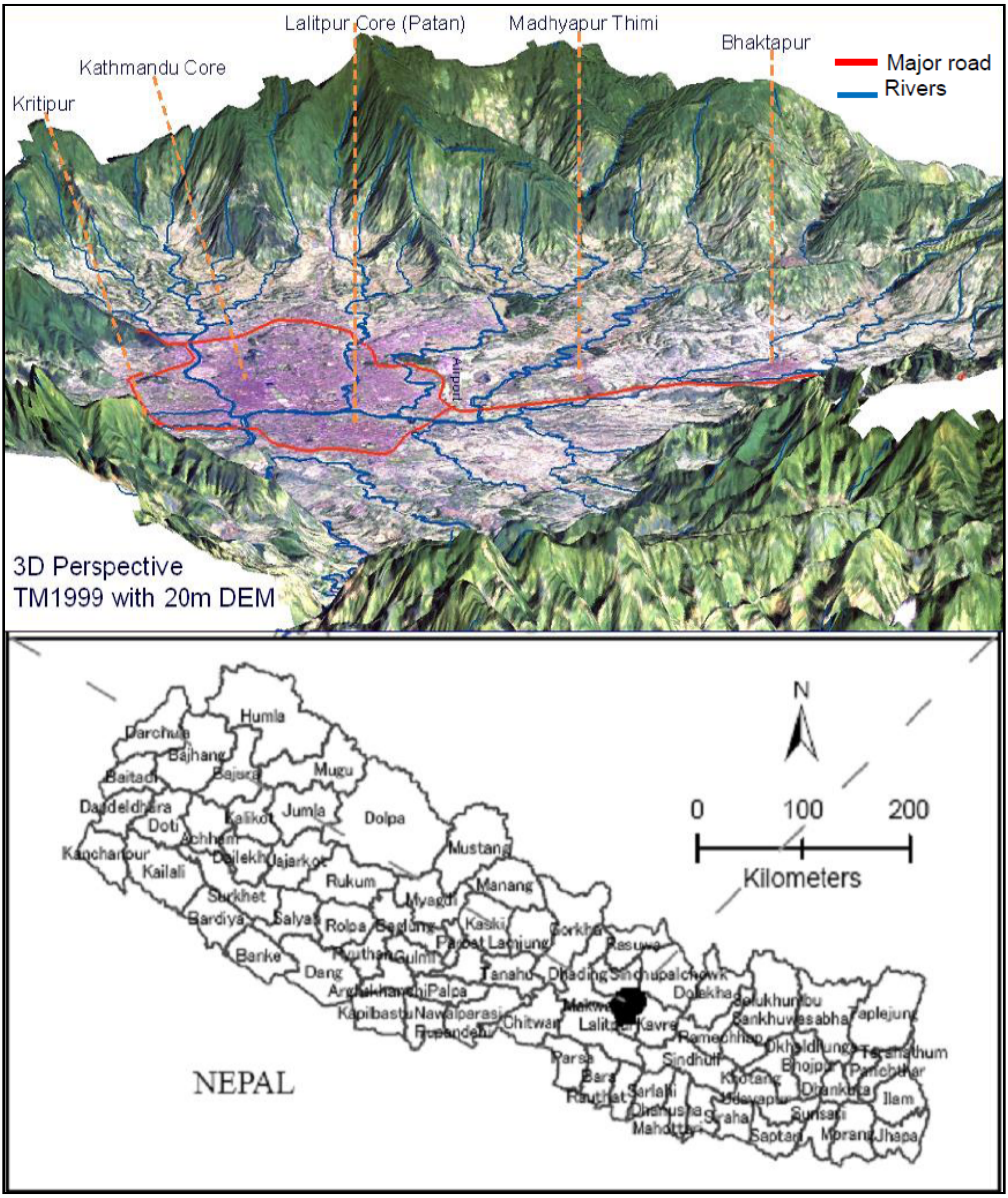
Figure 2. A perspective view of urban landscape development in Kathmandu Valley (Photo by author, fieldwork, 2007).

2. Research Methodology

2.1. Study Area

Physiographic boundaries formed by the complex topography play an important role in allocating development resources. Therefore, the valley as a study area in this research is delineated based on the watershed boundaries, which were derived from 20-meter digital elevation point data (Figure 3).

Figure 3. Study area–Kathmandu Valley.



The elevation in the valley ranges from 1,100 to 2,700 meters above the sea level, and forms complex topography within a small geographic area. Half of the study area has slopes of less than 5 degrees, while more than 20% of the land has slopes greater than 20 degrees. Geographically, the valley is situated between 27°31′55″ to 27°48′56″ North latitude and 85°11′11″ to 85°31′52″ East longitude. The valley is drained by the Bagmati river system. The river system is the main source of water for drinking and irrigation in the valley [3,23]. Politically, the valley is composed of five municipal urban centers (Kathmandu, Lalitpur, Bhaktapur, Kirtipur, and Madhyapur Thimi), in addition to 97 surrounding villages. The study area covers 684 km^2, and the urban centers make up only 14% of the land.

2.2. Data Sources

Remote sensing provides spatially consistent data sets that cover large areas with both high spatial details and high temporal frequency [12,15]. Dating back to the 1960s, remote sensing can also provide consistent historical time series data. Because of the lack of temporal and spatially consistent datasets in other forms for the valley, multi-temporal satellite images with high resolution (CORONA, SPIN, and IKONOS) to moderate resolution (LANDSAT MSS and TM) were processed to identify the temporal changes in landscape patterns since the 1960s. The high resolution images are only available for limited areas in the valley; therefore, most care was given to the LANDSAT MSS and TM images. Because of the mountainous terrain and topographic complexity in the study area, the elevation data was also considered as an important source of information. Fieldwork was conducted in December 2007 to acquire first hand the data required for the research. A detailed list of the data used in this study is shown in Table 1.

Table 1. List of databases used in this research.

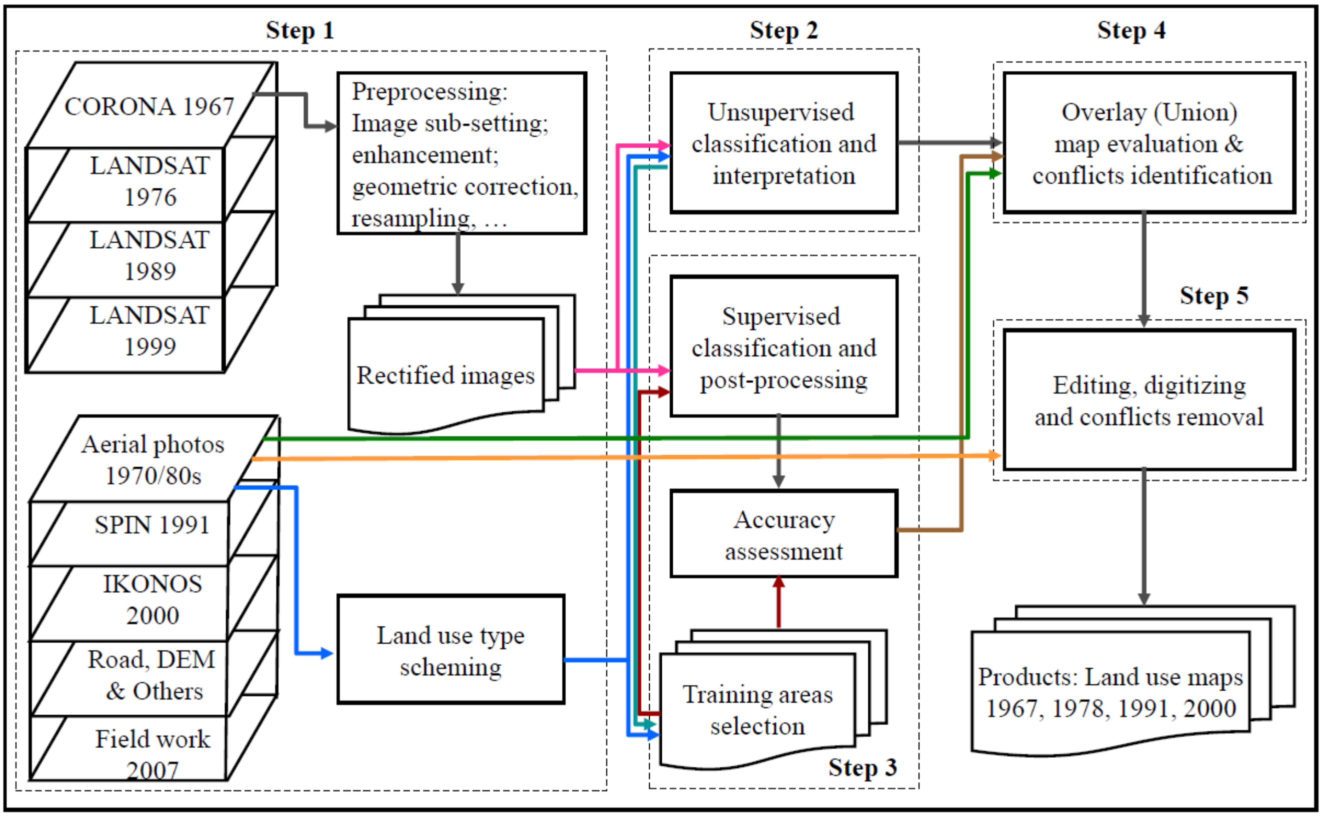
Data types	Year	Resolution/scale	Sources
Satellite imageries:			
CORONA	1967.02.05	1 Meter	USGS
LANDSAT MSS	1976.10.28	57 Meter	University of Maryland
LANDSAT TM	1989.10.31	30 Meter	University of Maryland
SPIN-2	1991 *	2 Meter	USGS
LANDSAT TM	1999.11.04	30 Meter	University of Maryland
IKONOS	2000 *	1 Meter	GeoEye, Space Imaging
QuickBird	2007 *	0.6 Meter	Google Earth
Aerial photographs	1979, 1981, 1992, 1998	-	Survey Department, Nepal
Vector layers:			
Spot height (points)	1995	20 Meter	[24]
Land cover map	1978	-	
Land use map	1995	1:25000	
Road map	2000	-	
Field survey (geographic references, observations and interviews)	2007.12	-	Kathmandu fieldwork

* The data acquisition date (month and day) is missing.

2.3. Mapping of Spatial Patterns

The satellite data are in image form and contain many details, but not in an objective thematic setting. Image analysis techniques are evolving rapidly, but many operational and applied remote sensing analyses still require extracting discrete thematic land surface information from satellite imagery using classification-based techniques [7,25]. Prenzel and Treitz [26] and Thapa and Murayama [15] argued that the heterogeneity and complexity of the landscape in urban regions, for example, suburban residential areas forming a complex mosaic of trees, lawns, roofs, concrete, and asphalt roadways, require land use and land cover classification techniques that combine more than one classification procedure to improve remote sensing-based mapping accuracies. Therefore, a series of processing steps (Figure 4) is followed to transform those data into meaningful thematic information.

Figure 4. Land use mapping scenario for remote sensing images.



The geometric rectification process was carried out for all satellite images using a road network map in the local projection system (i.e., UTM WGS 1984). Image enhancement, contrast stretching, and false color composites were created to improve the visual interpretability of the image by increasing the apparent distinctions between the features. Knowledge-based visual interpretation, texture, and association analysis were performed at the preliminary stage. Furthermore, field survey data, aerial photographs, high resolution satellite images, and city planning documents were carefully analyzed while preparing the land use classes. After analyzing all the information collected so far, only twelve types of land uses were considered for mapping, i.e., agricultural areas, forest, shrubs, open space, water, built-up areas, industrial areas, roads, airport, institutional areas, government secretariat area, and royal palace. The last six land uses cover small spaces in the valley; therefore, these land uses were merged into an urban/built-up area category for detailed quantitative assessment purposes. However, all twelve legend units were listed in the land use maps.

CORONA image was resampled using a nearest neighbor resampling technique to match the data resolution of LANDSAT (30-meter) for maintaining spatial resolution consistency in the data sources. Resampling the CORONA image (1-meter) into 30-meter may introduce modifiable areal unit problem (MAUP) due to generalization of continuous geographical phenomenon as discussed by Openshaw and Alvanides [27]. When values are averaged over the process of aggregation, variability in the CORONA image is lost which may result the variation in spatial patterns arising from the statistics computed at coarser resolution. This problem is also known as scale effect in MAUP. However, after following the steps shown in Figure 4, such problem will be removed in resulting map.

An unsupervised approach with the ISODATA clustering technique [28] available in Erdas Imagine 9.0 was applied to obtain different land use clusters of similar spectral pixels in the Corona, MSS and TM images. This preliminary interpretation reduced the artificial errors and selected the most appropriate clusters for further processing. Then, the supervised approach with the maximum likelihood parameter was run to improve the accuracy of the land use classification for the images for all three dates (1967, 1976, 1989, and 1999). Aggregating the detailed remotely sensed surface characteristics into thematic information always contains some degree of errors, hence, an accuracy assessment should be performed [14,15]. The image classification accuracy was performed by evaluating the overall classification accuracy using geographically referenced vector datasets. The classification accuracies of 83.66, 80.66%, 84.44%, and 83.33% were achieved for the years 1967, 1976, 1989, and 1999, respectively.

Because of the complex topography in the valley, land use types are closely related to altitude and slope and have some specific distribution rules. Confusing areas were detected mostly between the water areas and shadows of mountain areas; bare lands, brick factories, and construction sites; and golf courses and shrub lands. The areas of confusion were further verified with DEMs and slope data, road data, the 1978 land cover map, high resolution imagery, including CORONA (1967), SPIN (1991), IKONOS (2000), aerial photographs acquired at different time periods, and fieldwork information to determine the appropriate land use type. Editing and digitizing were carried out to resolve all the confusion and conflicts that occurred in each map. This process helped to improve the accuracy of the mapping. After updating the maps, the reference year of each map was fixed to 1967, 1978, 1991, and 2000, respectively.

2.4. Analysis of Spatial Patterns

The land use transition matrix is a useful tool that has been widely accepted in land use change analysis [11,16]. Three land use transition map layers for the years 1967–1978, 1978–1991, and 1991–2000 were prepared for the detailed land use change pattern analysis in the valley.

Empirical studies have substantiated the use of both spatial metrics and remote sensing in urban modeling [10,11]. The use of spatial metrics has provided a new platform for describing the spatial land use and land cover heterogeneity and morphological characteristics within the urban environment. Spatial metrics are already commonly used to quantify the shape and pattern of landscapes [11,29,30].

Recently, there has been an increasing interest in applying spatial metric techniques in an urban environment to link land use heterogeneity to structures and dynamic changes in urban land uses [10].

Table 2. Description of spatial metrics used in this study (Compiled from [30]).

Metrics	Description	Units	Measure of
PD	PD equals the number of patches of a specific land cover class divided by total landscape area.	No./ 100 ha.	fragmentation
ED	The sum of the lengths of all edge segments involving a specific class, divided by the total landscape area multiplied by 10000.	Meters/ ha	fragmentation
LPI	The area of largest patch of the corresponding class divided by total area covered by that class, multiplied by 100.	Percent	dominance
ENNMN	The distance mean value of all patches of a land use to the nearest neighbor patch of the land use based on shortest edge-to-edge distance from cell centre to cell centre.	Meters	isolation/ proximity
AWMPFD	It describes the complexity and fragmentation of a patch by a perimeter-area ratio. Lower values indicate compact form of a patch. If the patches are more complex and fragmented, the perimeter increases representing higher values.	None, range: 1-2	fragmentation and complexity
COHESION	Approaches 0 as the portion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected.	None, range: 0-100	physical connectedness
CONTAG*	Contagion index describes the fragmentation of a landscape by the random and conditional probabilities that a pixel of patch class is adjacent to another patch class. It measures to what extent landscapes are aggregated or clumped.	None, range: 1-100	fragmentation and the degree of aggregation
SHDI*	Shannon's diversity index quantifies the diversity of the landscape based on two components: the number of different patch types and the proportional area distribution among patch types.	Information	patch diversity

PD: patch density; LPI: largest patch index; ED: edge density; AWMPFD: area weighted mean patch fractal dimension; ENNMN: Euclidian nearest neighbor distance mean; CONTAG: contagion; SHDI: Shannon's diversity index. * Metric can be applied only for landscape level assessment [30].

A set of spatial metrics were selected to measure and monitor the landscape fragmentation, land use complexity, proximity, dominancy, and diversity (Table 2). The selected metrics are patch density (PD), largest patch index (LPI), edge density (ED), area weighted mean patch fractal dimension (AWMPFD), Euclidian nearest neighbor distance mean (ENNMN), cohesion (COHESION), contagion

(CONTAG), and Shannon's diversity index (SHDI). These metrics describe the composition and configuration of landscape pattern changes in the valley.

The metrics were computed for each land use map at the class and landscape levels. Metrics at the class level are helpful for understanding landscape development, while those at the landscape level provide relatively general information on the assessment [31]. All these metrics were calculated using the FRAGSTAT software [30] while Erdas Imagine and ArcGIS software were used for image analysis and GIS data processing.

3. Results

3.1. Spatial Patterns of Land Use

Land use statistics and transition matrices are important information to analyze the temporal and spatial changes of land use, and examine the driving forces behind those changes. Figure 5 shows the four land use maps for the years 1967, 1978, 1991, and 2000. The urban/built-up areas in the valley had a noticeable increase, from 3% (2,010 ha) of the total land in 1967 to 14% (9,717 ha) in 2000, showing spatial patterns of urbanization with consistent (5%) growth in 1991 and 2000 (Table 3). However, an opposite trend in shrubs (13,563 ha) and forest (15,800 ha) lands was observed, where half of the shrubs land changed to another class by 2000, including a significant loss of area between 1978 and 1991. Similarly, the forest lost 4% of its land over the three and a half decades. However, after gaining a small area in 1978, the forest lost land area in later years.

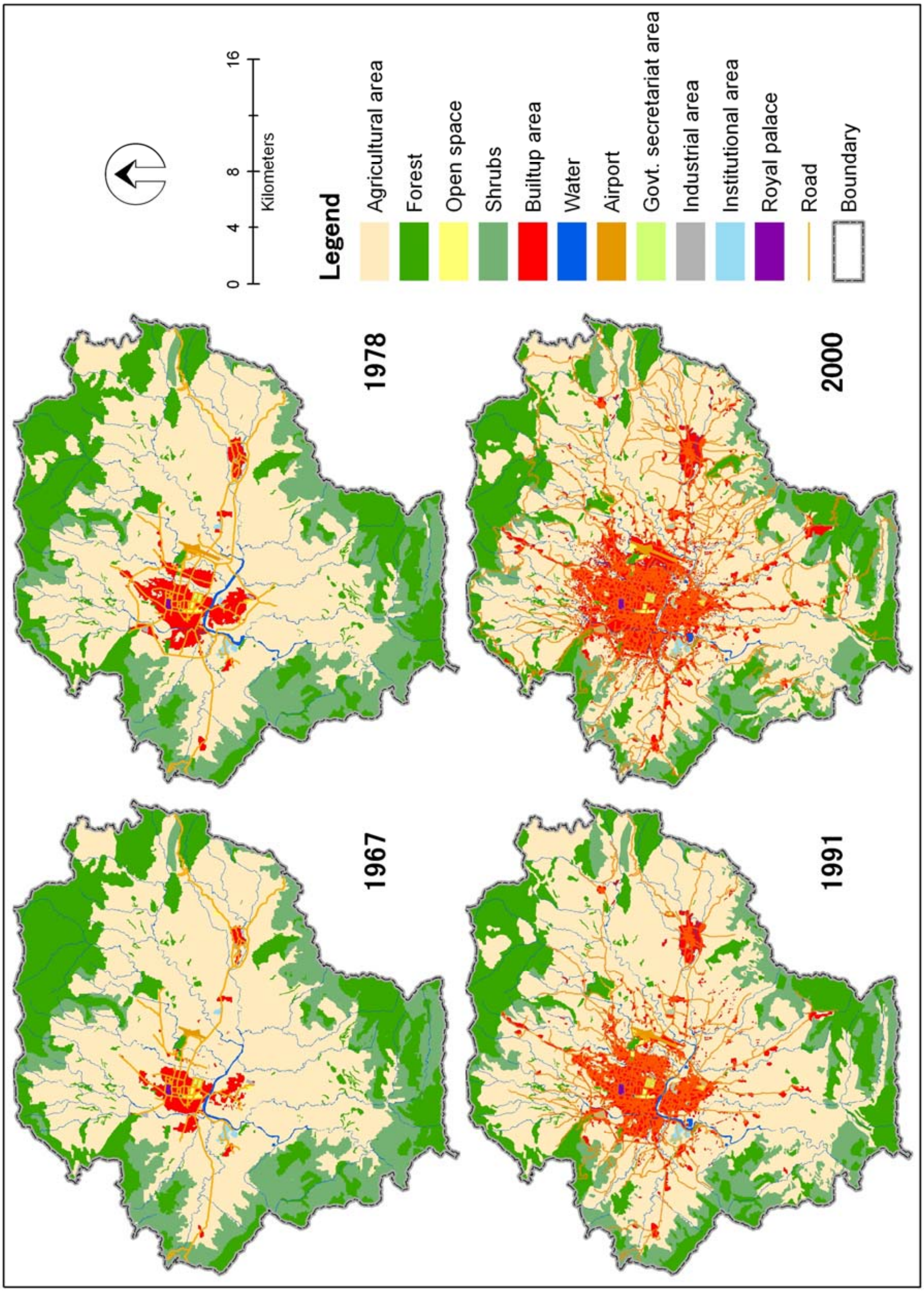
Table 3. Land use statistics.

Year	**1967**		**1978**		**1991**		**2000**	
Land use type	Hectare	%	Hectare	%	Hectare	%	Hectare	%
Shrubs	13563	19.81	12124	17.71	8129	11.87	7150	10.44
Forest	15800	23.08	16311	23.83	13887	20.29	13301	19.43
Water	1337	1.95	1380	2.02	1341	1.96	1266	1.85
Urban/builtup area*	2010	2.94	3362	4.91	6313	9.22	9717	14.19
Open Space	100	0.15	95	0.14	135	0.20	171	0.25
Agricultural area	35649	52.07	35186	51.40	38652	56.46	36854	53.83
Total	68458	100.00	68458	100.00	68458	100.00	68458	100.00

* Includes builtup areas, industrial areas, roads, airport, institutional areas, government secretariat area, and royal palace (Figure 5).

Agricultural lands still cover half of the valley, but their area has increased and decreased in different time intervals. The agricultural land decreased slightly by 1978, but increased to 56% of the total land by 1991, and had again decreased to 54% in 2000. Only 2% of the total land in the valley is covered by water. A few manmade ponds and the Bagmati river system are the major components of the water coverage. Because water covers a small area, only a small pattern of change was found for water. Similarly, the availability of open spaces for recreation and sports purposes in the valley is observed to be very low.

Figure 5. Land use maps (1967, 1978, 1991, and 2000, modified from [13]).



3.2. Spatial Patterns Changes

Figure 6 shows the landscape transition maps for the three time periods. The maps demonstrated significant landscape transitions during the study period. Most of the agricultural lands in the valley floor and near existing built-up areas were transformed into urban/built-up lands, whereas shrubs and forest lands were converted into agricultural lands elsewhere in the rural periphery.

Three major land use transitions were observed during the period of 1967–1978 (Figure 6, Table 4). The agricultural lands (1.96% of the total land) in the valley floor, mostly in close proximity to the road and existing built-up periphery, were converted to urban/built-up areas. In the southwestern mountain landscape, much of the shrubs lands were converted to forest lands, while in the northeastern area the forest areas changed to agricultural lands. The transitions between the other land uses were found to be very small during this period.

A ring road around the existing urban core was built during the 1970s. This road significantly enhanced the urbanization process in later decades, which can be easily discerned during the years 1978–1991 (Figure 6). The agricultural lands near the road began to be transformed to urban/built-up areas. During this period, a significant amount of agricultural land (3.9%) was changed to urban built-up lands, with urbanization following the road networks and existing built-up peripheries (Table 5). In the meantime, the other land uses also contributed to the urbanization process at lower rates. Large proportions of shrubs (5.3%) and forest (3.8%) lands were transformed into agricultural land in the surrounding rural mountain areas in the valley. This can be observed mostly in the northeastern border of the valley, and may be due to conversion of agricultural lands to built-up areas in the urban fringes, which forced the farmers to migrate in vicinities in one hand. On the other hand, due to road expansion and market accessibility to rural areas, farmers were encouraged to develop agricultural activities in the rural hills and had spread on the nearby shrubs and forest lands.

The land use transition continued in 1991–2000 (Figure 6). A different phenomenon of land conversion is observed in this period as compared to the earlier time period. The transformation of agricultural land into urban/built-up areas was increased (4.4%), but the transformation of the other land uses into agricultural lands remarkably decreased (Table 6). However, agricultural encroachment on shrubs lands still continued at slow rate as compared to earlier. Forest (0.36%) and shrubs (0.19%) lands were also changed to built-up areas as a result of the expansion of rural roads in the 1990s.

Figure 7 shows the transition of urban built-up areas over the other land uses as a whole for the last four decades, which makes the spatial patterns of urbanization clearer. The spatial pattern of urban growth is observed at different forms at different time in different places. Larger clusters away from the urban areas can be discerned until 1978. The start of agglomeration between the urban patches is noticed in the 1990s. Refill development connecting the several urban fringe patches and more heterogeneous landscape development in the existing built-up periphery can be observed by 2000.

Figure 6. Land use change in different time periods (1967–1978, 1978–1991, 1991–2000, and 1967–2000).

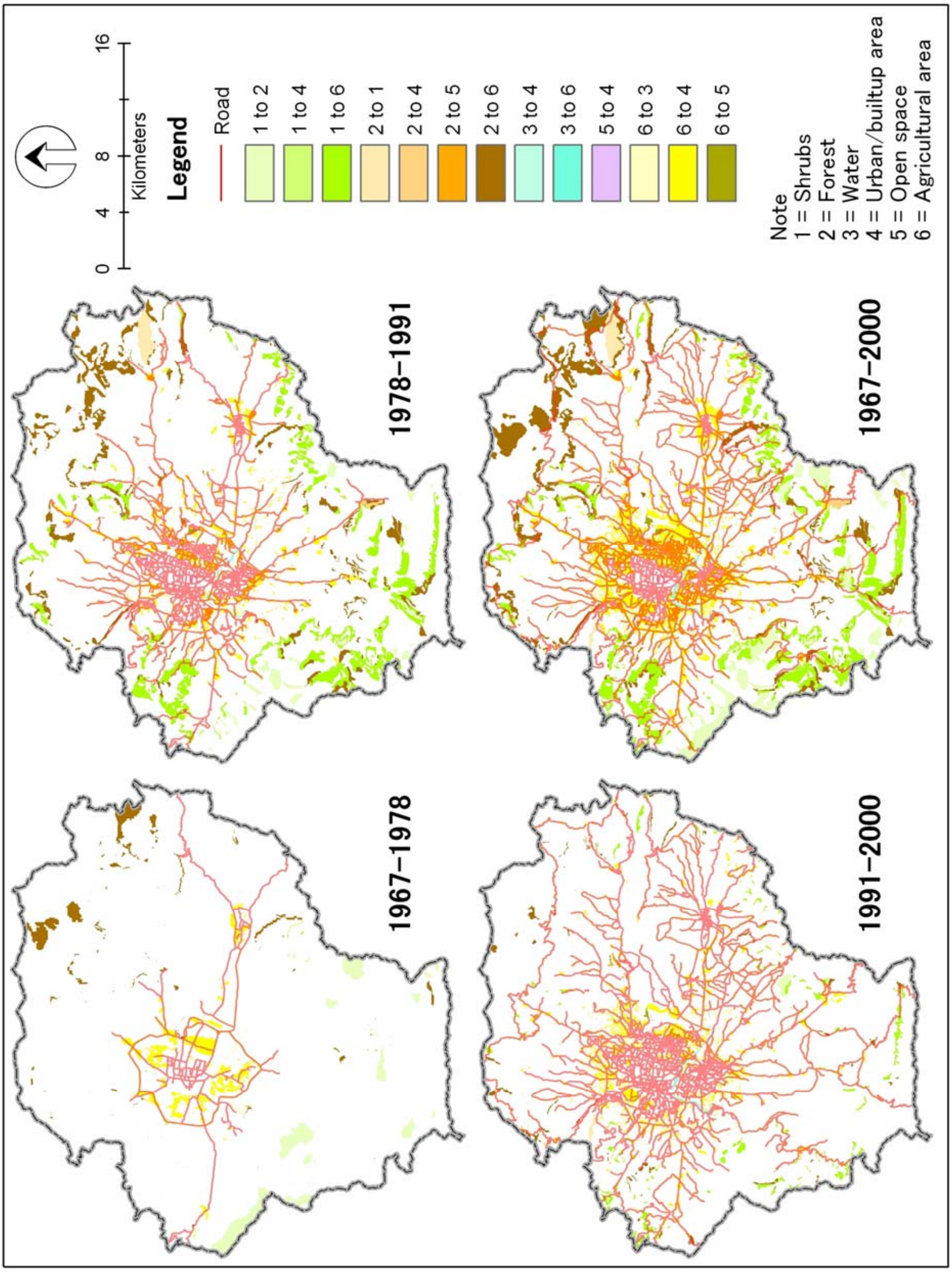


Table 4. Land use change in percentage (1967–1978).

	1978						
1967	Shrubs	Forest	Water	Urban /builtup area	Open space	Agricultural area	Total
Shrubs	17.68	2.13	0.00	0.00	0.00	0.01	19.81
Forest	0.03	21.70	0.01	0.01	0.00	1.33	23.08
Water	0.00	0.00	1.95	0.00	0.00	0.00	1.95
Urban/builtup area	0.00	0.00	0.00	2.93	0.00	0.00	2.94
Open space	0.00	0.00	0.00	0.01	0.14	0.00	0.15
Agricultural area	0.00	0.00	0.06	1.96	0.00	50.05	52.07
Total	17.71	23.83	2.02	4.91	0.14	51.40	100.00

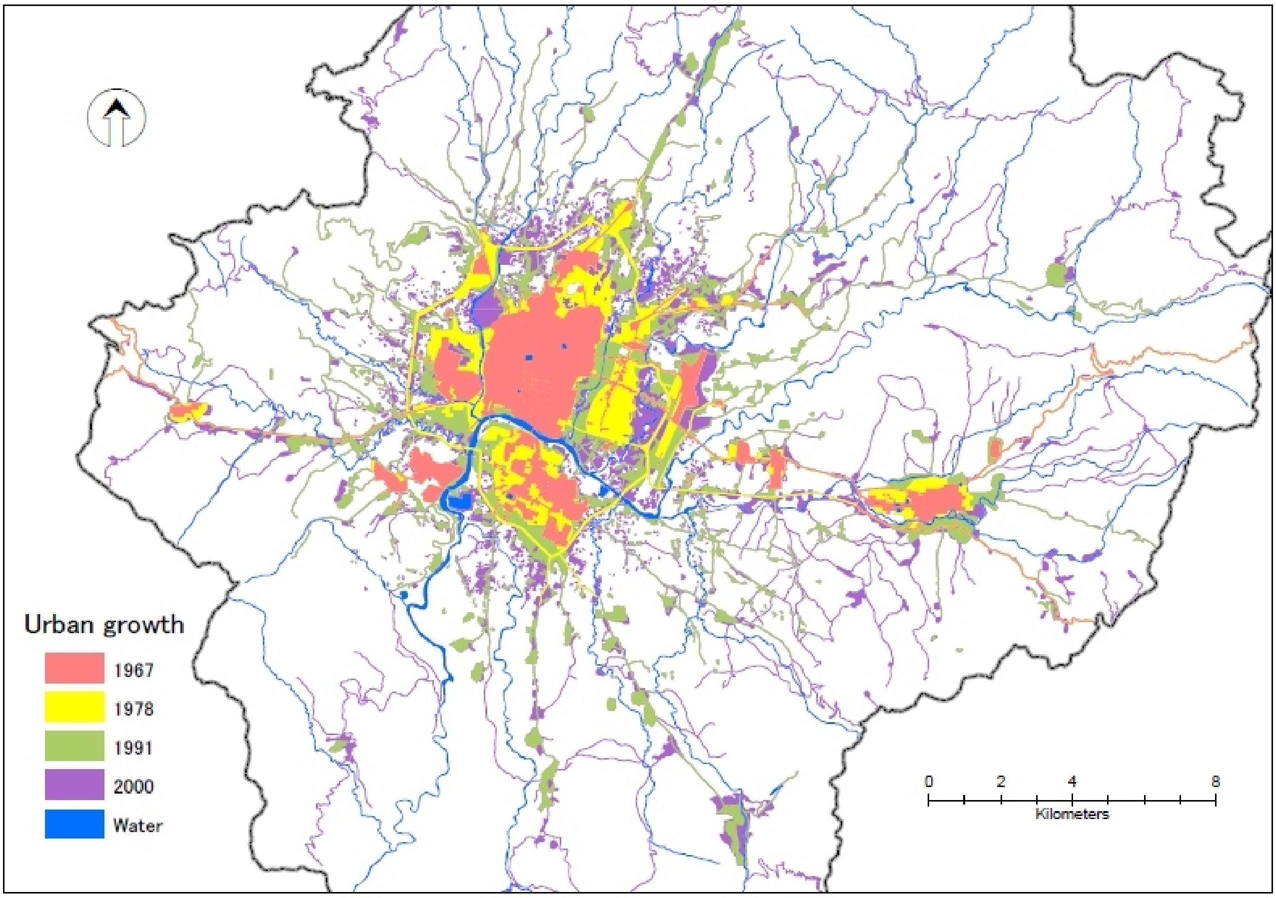
Table 5. Land use change in percentage (1978–1991).

	1991						
1978	Shrubs	Forest	Water	Urban /builtup area	Open space	Agricultural area	Total
Shrubs	11.41	0.89	0.00	0.13	0.00	5.27	17.71
Forest	0.46	19.32	0.00	0.21	0.03	3.81	23.83
Water	0.00	0.00	1.92	0.04	0.00	0.06	2.02
Urban/builtup area	0.00	0.00	0.00	4.90	0.00	0.01	4.91
Open space	0.00	0.00	0.00	0.03	0.10	0.00	0.14
Agricultural area	0.00	0.07	0.04	3.90	0.07	47.32	51.40
Total	11.87	20.28	1.96	9.22	0.20	56.46	100.00

Table 6. Land use change in percentage (1991–2000).

	2000						
1991	Shrubs	Forest	Water	Urban /builtup area	Open space	Agricultural area	Total
Shrubs	10.35	0.12	0.00	0.19	0.00	1.21	11.87
Forest	0.08	19.23	0.00	0.36	0.04	0.57	20.29
Water	0.00	0.00	1.84	0.03	0.00	0.09	1.96
Urban/builtup area	0.00	0.01	0.00	9.19	0.01	0.01	9.22
Open space	0.00	0.00	0.00	0.02	0.18	0.00	0.20
Agricultural area	0.01	0.07	0.01	4.40	0.02	51.95	56.46
Total	10.44	19.43	1.85	14.19	0.25	53.83	100.00

Figure 7. Spatial patterns of urbanization in Kathmandu Valley.



3.3. Landscape Fragmentation and Heterogeneity Analysis

Planners and policy makers are normally concerned about the negative effects of landscape fragmentation and heterogeneity development. There are two processes that can result in these effects, namely the reduction of the total amount of land with a specific land use (decrease in size), and the breaking up of land use into smaller patches (increase in isolation of the land use patches). This process will also be followed by an increase in the total amount of edges in some cases. Agricultural expansion in the rural areas, urban development, and transportation infrastructure development in the valley floor over time are regarded as the main processes that influence landscape fragmentation and heterogeneity development.

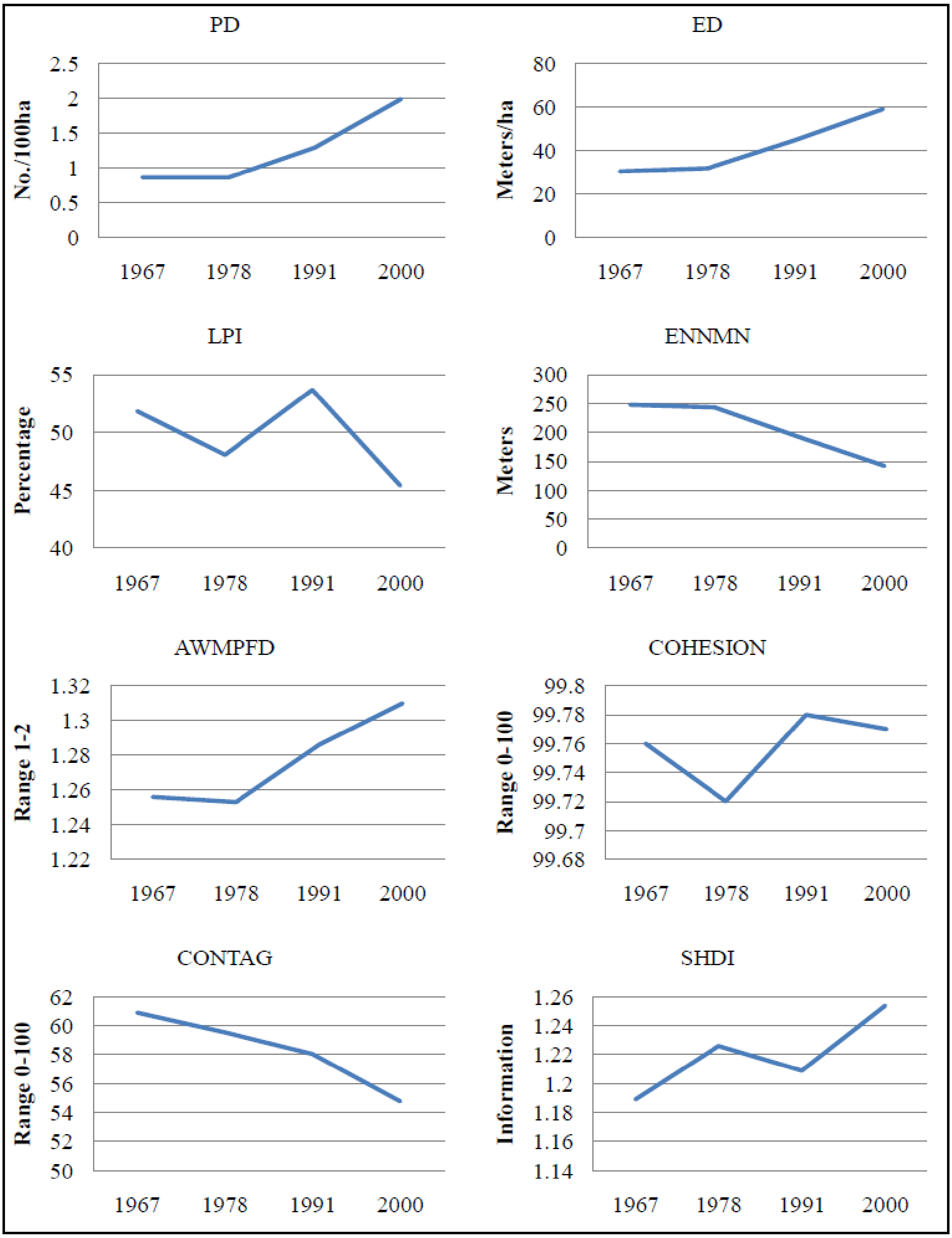
Landscape level analysis: At the landscape level, the patch density (PD) in the valley increased from 0.86 in 1967 to 1.99 in 2000 (Figure 8). The number of new patches in the landscape significantly increased since 1991. The increase of PD often leads to increased edge density (ED), as it creates new edge segments in the patch. The ED almost doubled in the whole study period, increasing steadily in the 1980s and 1990s after a small increase in the 1970s. Edge density often increased while land use fragmentations occurred due to land use changes. In the valley, it is observed mainly in the urban built-up areas, and the agricultural area particularly increased in the 1980s and 1990s, as shown by the figures of PD and ED. However, the dominance index (LPI) slightly increased in 1991 but decreased in 2000. The land use compactness of the urban/built-up areas in the valley floor and the expansion of agricultural activities into shrubs and forest lands, forming larger patches in the landscape in the 1980s and 1990s (Figure 5), can be commonly observed.

A significant amount of agricultural lands, i.e., 4.4%, was transformed into urban/built-up area during the period 1991–2000 (Table 6, Figure 6), which reduces the proximity (ENNMN) of the neighboring land use patches. The ENNMN decreases across the whole study period. The expansion of urban/built-up areas in the existing built-up periphery in the valley floor and agricultural encroachment near shrubs and forest lands in the rural areas could be the main causes of the ENNMN decline in the 1990s.

The AWMPFD increased slightly, reporting the degree that the shapes of the patches became more complex in later years. This may be due to road network expansion towards the rural areas in the 1980s and 1990s. A decreasing trend is observed in CONTAG, which shows the growing dispersion and fragmentation of the urban/rural landscape in the valley. The physical connectedness of the land use in 2000 increased as compared to 1967, but it faced some increases and decreases in the 1970s and 1980s, as shown by the COHESION index.

The diversity of land uses in the valley also increased. Construction of additional bridges over the rivers and the expansion of urban/built-up areas over the agricultural land in fringe areas and the beyond in the valley played key roles in increasing the heterogeneity of the landscape. However, the construction of commercial complexes and planned residential developments, represented by the built-up area in the maps, in the valley floor increased in recent decades, but their impacts on improving homogeneity at the landscape level are small. A temporal reduction of the contagion (CONTAG) and an increase of the patch diversity (SHDI) presented a clear picture of increasing the landscape heterogeneity in the valley.

Figure 8. Spatial metrics at landscape level.



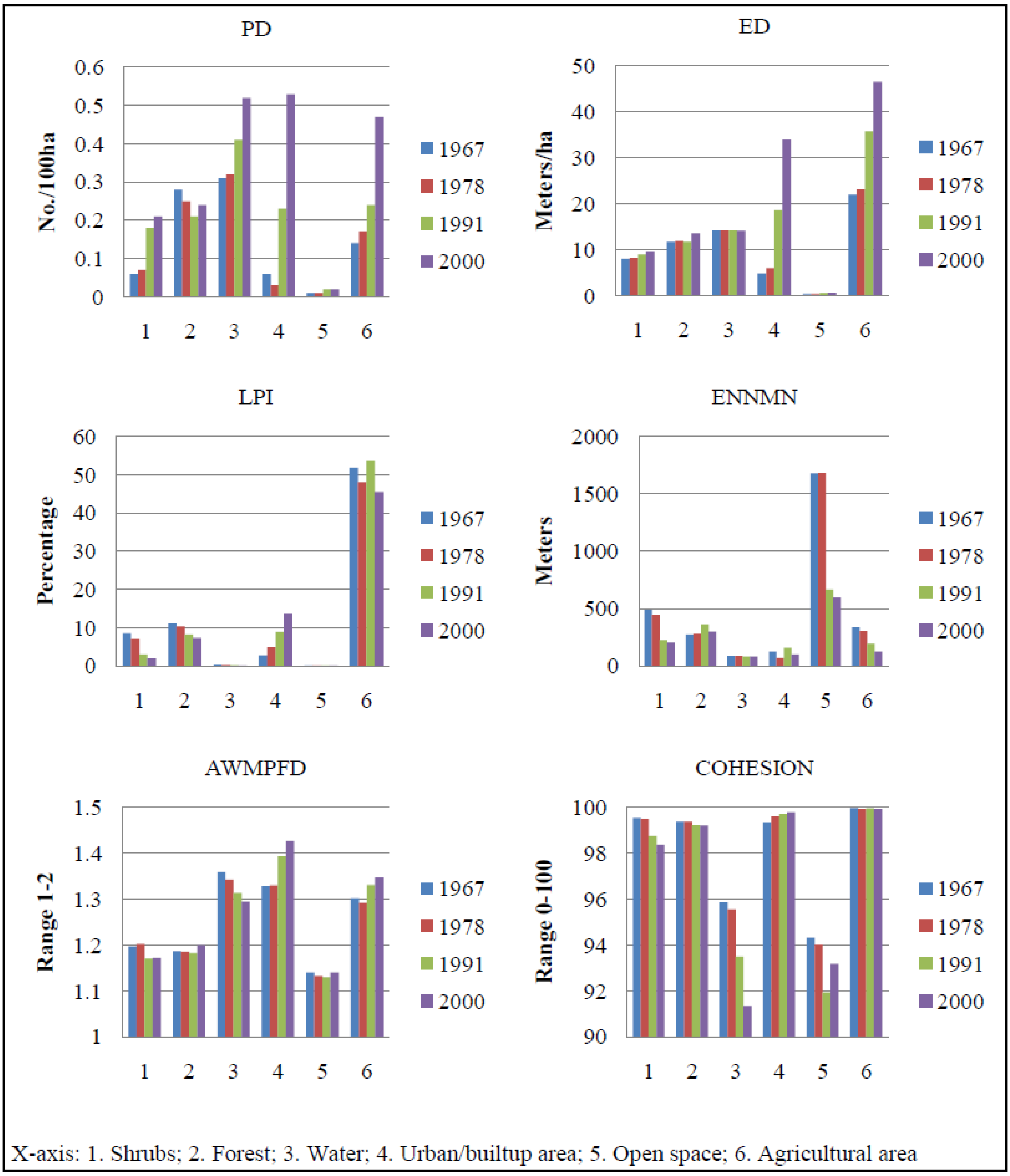
Class (land use) level analysis: At the class level metrics, changes in the PD of all land use classes are observed, except in the forest land cover (Figure 9). The PD of urban/built-up and water areas had remarkable changes in the 1980s and 1990s. The proportions of these land uses are small in the valley as compared to the other major land uses. Due to the inconsistent widths and linear character of the rivers, construction of additional bridges over the rivers in the later decades might have influenced the increase in the PD of water areas. The increase of PD in urban/built-up areas is a result of the urbanization process that occurred rapidly in the 1990s. The population influxes into the valley floor increased the demand for new housing, subsequently creating new built-up areas in the city fringes that segmented the existing agricultural lands in the later years. This process also increased the PD and ED of urban/built-up areas, including agricultural areas. The ED of agricultural land remained higher than that of other land uses. However, this dominancy could cause higher ED values, as shown by the LPI. A noticeable change is observed in the ED and PD of agricultural and urban/built-up land uses correlating each other in the 1980s and 1990s. The trend of unordered individual housing development in the valley floor, especially in the fringe areas in the corresponding decades enhanced the fragmentation and the heterogeneous landscape development.

A gradual increase in LPI is found for the urban/built-up land use type. The increasing intensity of buildings and other infrastructure in the core area in the 1990s, for example, increased the LPI of the urban built-up area. In the same time-frame, the LPI of agricultural land decreased significantly, showing a tremendous urbanization pressure over the agricultural lands, as observed in Figure 6. The urbanization process over agricultural land is a common trend in the valley. However, the LPI of other land uses decreased. The expansion of urban infrastructure abutting the land between the built-up areas and surrounding areas in the valley floor in the later decades (Figure 7) is the main cause of the improvement of the dominance index of the urban/built-up areas.

Adding new urban structures in agricultural spaces creates new patches, eventually fragmenting the land in both categories and reducing the proximity (ENNMN) between the neighboring patches of similar land uses. This occurred mostly in the agricultural land in the valley. A decreasing trend is observed over the whole study period. It is true that when urbanization activities occur in agricultural land, for example the development of road networks, open spaces, or even individual buildings, it creates a patch for the infrastructure itself and divides the agricultural lands into two patches. This process decreases the ENNMN of agricultural land patches, creating several patches within close proximity. Interestingly, a decrease of ENNMN for urban built-up areas in the 1970s shows that the urbanization process was confined mostly in the margins of the existing built-up areas. In the 1980s, ENNMN increased, which shows the start of the urbanization process away from the city core, i.e., rural areas (Figure 6). The distance (ENNMN) between the patches of open space significantly decreased in 1991 and 2000. This was due to expansion of existing open spaces and the addition of new open spaces such as golf courses in the valley.

The AWMPFD always remained higher in water areas as compared to the other land use types, reflecting the complex shape of the rivers. This is somewhat natural, as rivers pass through complex mountain topography in the valley. The shape complexity of urban/built-up lands significantly increased in later decades. Expansion of roads into rural areas could be a cause of this. The agricultural land still has simple shapes compared to the other land uses in the valley, although the trend of shape complexity has gradually increased. Based on the COHESION index, the agricultural land use has a higher degree of physical connectedness than the others. The degree of physical connectedness of urban/built-up areas also gradually increased over time. The merging of built-up areas between the previously separated urban structures in close proximity to roads, especially in the city core and fringe areas, could result in such an increase.

Figure 9. Spatial metrics at class level.



4. Discussion

The spatiotemporal analyses clearly showed that the intensity of human induced activities (Figure 2) affected the landscape pattern of the study area. However, the other important finding was that it also influenced the dynamic changes in the land use types. The rapid urbanization process over productive agricultural lands in close proximity to the road network in the valley is apparent. The built-up area increased by 5% in each decade of the 1980s, and 1990s. This rate of increase is much higher than in the United States, Canada, and New Zealand [17].

A large share of agricultural space was transformed to urban/built-up areas in different time periods, and this mainly occurred in the valley floors and neighboring villages. A proportional transition of other land uses to the urban/built-up areas was also found to be consistently increasing. Interestingly, a significant level of agricultural encroachment over the shrubs and forest lands was found in the 1980s. The urbanization process resulted in the increase of agricultural activities in rural areas in the valley. This is a common phenomenon near metropolitan regions of developing countries [31].

The urbanization process in the valley has caused fragmentation of the landscape and heterogeneous land use development. Haphazard land development practices and uncontrolled urban growth enhance those processes and generate a range of environmental problems, water shortage, air pollutions in the lack of green space, for example, affecting human health and welfare. The demand for infrastructure and services has caused the emergence of a number of urban environmental problems in Kathmandu [3]. However, the heterogeneous landscape development will continue into the next few decades as the built-up areas in the valley floor have already started to agglomerate. Planned residential developments are emerging recently in the fringe and rural areas. Furthermore, the decreasing trend of nearest neighborhood distance is an indication that homogeneity will increase by refill type development after a certain period of time.

A significant extension of the road network is observed during the 1980s and 1990s. The development of road networks to the rural periphery in the valley reduced the travel time for commuters living in the villages. It made it easier for rural farmers, the sole producers of the perishable goods for urban dwellers in the valley, to commute to the city for urban services and markets. This process enhanced rural prosperity and attracted migrants from neighboring districts. The rural villages gradually become urban frontiers. Along with the increased income, the agricultural landscapes in close proximity to the roads were gradually converted to urban/built-up areas, stretching the urbanization influences to rural areas. Many individual developments occurred nearby in later years, showing that travel time was probably a major driver of change. Usually, the influence of roads is not linear. Bruijn [32] indicated that the factors influencing land development probabilities often have a strong ‘distance decay function’. For example, the influence of a road or existing built-up areas on land development decreases quickly with distance.

The land use change maps show that the most productive agricultural lands are now being converted to urban uses, particularly in the valley floor and nearby hills. This pattern is driven, in part, by migration [6]. Migrants tend to move to areas in close proximity to economic opportunities and urban services in the valley, which is usual in most developing countries in Asia [18]. Consequently, urban centers emerge from areas where people first moved to the land with highest productivity. From the field observations, most of the lands in the fringes and nearby villages are growing high value agricultural products (i.e., vegetables, flowers, and fruits), where they used to be rice paddies a few years ago. Some of the paddy terraces in the hills of the city fringes, most with easy access to water and roads, were converted to perishable agricultural production land. Many rice paddies were converted to other types of agricultural land use for better revenue under the influences of market mechanisms. Most of the urban structures in the valley are built by bricks (Figure 2). Due to high demand of bricks, the rice paddies having suitable soils for brick production in the fringe and rural areas have also been converted to brick kiln areas in the dry season and back to rice paddies in the rainy season [23].

Industrialization also contributed to the urbanization of the valley, particularly in the 1970s and 1980s [33,34]. Three major industrial estates, Balaju, Patan, and Bhaktapur, and several small scale industries scattered around the ring road and along major highways were established in the valley during these decades [3]. The carpet industry was one of the industries that flourished in the valley. High worldwide demand for Nepalese carpet in the 1980s and early 1990s encouraged entrepreneurs to make investments in this sector. By that time, 5,000 carpet factories were established in the valley, producing over 300,000 jobs [33], which enhanced the population pressure in the valley. This fact shows that the carpet industry may have been a major driving force of urbanization in the 1980s. At present, however, due to the unfavorable environmental consequences including water and air pollution, enforcement of environmental laws and public awareness in the valley has caused the decline of the carpet industry by 50% [35].

All these processes changed the spatial structure of the urban form in the valley floor, which is observed as a multiple-nuclei pattern. Furthermore, the urbanization process enhanced the fragmentation and heterogeneous landscape development in the valley as evident by the spatial metrics. The valley experienced high population influx and a heterogeneous land use environment caused by unrestrained urban development, which may pose serious threats to the inhabitants especially creating water shortages, human wastages, and more squatters [3].

5. Conclusions

In this study, we have investigated the spatiotemporal patterns of urbanization in the Kathmandu valley using remote sensing and spatial metrics techniques. The landscape of the valley is diverse and complex and comprises both homogeneous and heterogeneous surface features, which causes problems with the spectral variability in the satellite image data. The increasing population pressure caused the spatial pattern of urbanization to be highly dynamic. The predominantly agricultural landscape gradually changed to an urban landscape with increasing human settlement in the 1960s and 1970s. The changing process has escalated since the 1980s. It has proved to be very high in the urban fringe area. Spatial diffusion of urban/built-up areas has spread outward from the city core and along the major roadways.

The urban built-up area has increased by four times in the last four decades. Almost half of the shrubs land in the valley has disappeared during this period. Similarly, forest land decreased dramatically in the 1980s. Shrubs and forest landscape in rural areas of the valley mostly changed to agricultural areas. Half of the land in the valley is still agricultural area, but it has faced changing circumstances in different time period. Agricultural encroachment in rural hills and mountain peripheries and urbanization in the valley floor area are identified as the most common phenomenon in the study period. A small land use transition between the other land uses was also noticed.

The sparsely developed built-up area with individual unordered housing practices in the fringe areas indicated a complex urbanization process in the valley. An increasing trend of land use diversity is explored using the spatial metrics analysis. The land use patch density significantly increased during the period. Such urbanization process and scattered individual developments created fragmentation and a heterogeneous landscape that gradually increased in the 1980s and 1990s. These processes are mostly observed in the city fringes and adjacent villages in the valley. However, the overall nearest neighbor distance between the similar land use patches in the valley has decreased over the last two decades. The city core area seems to be agglomerated, which eventually creates homogeneity by the refilling type of development in future.

The study presented a consolidated approach of remote sensing and spatial metrics that allowed a separation of land use categories and descriptions of its temporal changes. It has provided a robust quantitative measure of land use dynamics using remotely sensed data for the last four decades of the 20th century, which will help urban planners and researchers to make assessments of landscape development and change.

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