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Urban land use change study in Ulaanbaatar city using RS and GIS

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Abstract: In recent years, Ulaanbaatar, the capital of Mongolia, has experienced very rapid urbanization. Different reasons are considered for urban expansion, however, the main cause is connected with a mass movement of rural people seeking for improved living conditions. The aim of this study is to analyse changes in urban land use in the central part of the capital city using remote sensing (RS) and geographic information system (GIS) datasets. For the development of the principal digital spatial database, a 1:5000 scale topographic map and a historical description of the elements of land use were used. To update the database and extract reliable urban land use information, very high-resolution panchromatic and multispectral Quickbird images of 2023 were fused. For fusion, three different data fusion techniques such as a Brovey transform, Gramme-Schmidt method and intensity-hue-saturation (IHS) transformation were compared in terms of the enhancement of spatial and spectral variations of the available classes. Of these methods, the IHS transformation gave a superior result in terms of both spectral and spatial separations between different objects and classes. Therefore, for this technique was selected for further analysis. Overall, the research showed that the central part of Ulaanbaatar city became very dense and precise planning should be considered.

Key words: Urban land use, RS image, Data fusion, Change study

1. Introduction

During the past decades, cities in both developed and developing countries have faced rapid growth due to considerable increase in world population and the permanent movement of people from country-side to city areas [1]. In most countries, people moved from countryside areas to cities seeking for the improved conditions that cities can offer. In 2011, the world reached a population of 7 billion. On 15 November 2022, the world population reached 8 billion people, a breakthrough in growth of humankind. Recent United Nations report has indicated that the world population is estimated to reach 8.5 billion in 2030, and to increase further to 9.7 billion in 2050, and 10.4 billion by 2100 [2].

Mongolia, as many other nations, has problems associated with the rapid increases in urban population and expansion. In Ulaanbaatar city, urbanization has become one of the country's serious issues. Today, Ulaanbaatar accounts for more than 48 percent of Mongolia's over 3.4 million population [3]. The main reason for urban sprawl in the country is mainly related to rural to urban migration, because cities have better living conditions, good infrastructure, and improved educational, social, cultural and health services. In addition, urban areas have more employment opportunities because of different ongoing and newly developed activities [1].

When rural people come from the countryside to cities, they usually settle in the ger districts, thus expanding cities and creating unplanned and underdeveloped neighborhoods. Recent statistics estimated that the ger area is now home to approximately 60% of Ulaanbaatar's total population. Only 10% of these areas have paved roads, which poses challenges related to public transportation, health services, and access to schools. Hazardous pollution in the city of Ulaanbaatar reached higher levels of particulate matter (PM) than concurrent data recorded in many other places and poses another problem for residents [4].

There are many studies on land use and cover changes related to the capital city of Ulaanbaatar. Amarsaikhan et al. (2000) conducted the first urban land use change study in Mongolia using remote sensing (RS) and geographic information system (GIS) datasets. In the study, the changes occurred in builtup and ger areas of Ulaanbaatar city were investigated in relation to the socio-economic reasons [5]. Chinbat et al. (2006) conducted the detailed land use and functional change studies in Baga toiruu area using a very high resolution satellite image and a large scale topographic map [6]. Amarsaikhan et al. (2011) studied the urban land use changes occurred in the capital city of Mongolia from 1930 to 2008 with a 10-year interval using GIS, Quickbird and TerraSAR data sets [7]. Byambakhuu et al. (2017) conducted a study on land use/land cover change detection and estimation of the areas for the trend of future using RS and statistical methods [8]. Myagmartseren et al. (2018) studied the growths of Ulaanbaatar city in two time series, 2000 and 2010 using fractal geometry, and concluded that the city is growing in a non-systematic and fractal way, even though the geometrical growth has not been strictly planned and has a most irregular shape of urban sprawl [9].

In most cases, to analyze the rapid changes, prevent a city from unplanned activities, and conduct appropriate planning, city planners need to frequently examine development and on-going processes using up-to-date maps. Such maps can easily be produced with the use of current very high resolution RS images having different spatial and spectral resolutions. Satellite RS has been widely used for urban study and change analysis [10-14]. As the present RS technology, methods, and methodologies are so advanced, it is possible to generate diverse thematic information at various scales and incorporate the generated information with the historical datasets and perform superior investigation [1].

The aim of this study is to analyze the urban land use changes occurred in central part of Ulaanbaatar city using very high resolution satellite and other datasets. For the study, the changes that occurred in the Ikh toiruu area during the centralized economy were compared with the changes that occurred during the market economy. For the creation of initial spatial and attribute databases, a topographic map of 2000 (scale of 1:5000) and the building attributes have been used. To update the created database of 2000 up to the present, multispectral and panchromatic bands of very high resolution Quickbird data of 2023 have been used. The final analysis was conducted using ArcGIS 10.2 and ENVI 5.2 systems and diverse techniques were applied.

2. Data sources and test area

2.1. Test Site and Data Sources

As a study area, the Ikh toiruu site of Ulaanbaatar city has been selected.

The study area chosen for the current study covers the central part of the capital city and has a ring structure [1]. In the area, one can define such land use classes as buildings, pedestrian walking area, road, bare soil, green area and central squire. However, the main aim of the study is to concentrate on the alterations of the building class.

As data sources, 1:5000 scale topographic (4 sheets) maps of 2000 and Quickbird data of 2023 have been used. The Quickbird data has four multispectral bands (B1: 0.45–0.52μm, B2: 0.52–0.60μm, B3: 0.63–0.69μm, B4: 0.76–0.90μm) and one panchromatic band (Pan: 0.45-0.9 μm) [1]. The spatial resolution is 0.63 m for the panchromatic image, while it is 2.44 m for the multichannel bands. In this study, the panchromatic band as well as green, red and near infrared bands, have been used.

3. Methodology

3.1. Georeferencing and Enhancement of the Images

Initially, the panchromatic band has been georeferenced to a Universal Transverse Mercator (UTM) map projection using 14 ground control points (GCPs) defined from a topographic map of the study site. The GCPs were selected on well defined sites of the selected image frame. For the transformation, a linear transformation and the nearest-neighbor resampling approach [15] were applied and the related root mean square error (RMSE) was 0.58 pixel. After that the coordinates of the multispectral bands have been transformed to the coordinates of the panchromatic band using the same number of GCPs, and the RMSE was 0.95 pixel.

The integrated image was then enhanced using some image fusion methods. The concept of image fusion refers to a process that integrates different images from different sources to obtain more information from a single and more complete image, considering a minimum loss or distortion of the original data [16]. In other words, image fusion is the integration of different digital images in order to create a new image and obtain more information than can be derived separately from any of them [17,18]. In our study, we used and compared such image fusion techniques as the Brovey transform, the Gramme-Schmidt method and the intensity-hue-saturation (IHS) transformation. Each of these techniques is briefly discussed below.

Brovey transform: This is a simple numerical method that is used to merge different digital data sets. The algorithm based on a Brovey transform uses a formula that normalises the multispectral bands used for a red, green, blue color display and multiplies the result by high resolution data to add the intensity or brightness component of the image [19]. The formulae used for the Brovey transform can be described as follows:

$$Red = \frac{Band1}{\sum_{i=1}^{n} Bandi} * HighResolutionBand$$

$$Green = \frac{Band2}{\sum_{i=1}^{n} Bandi} * HighResolutionBand$$

$$Blue = \frac{Band3}{\sum_{i=1}^{n} Bandi} * HighResolutionBand$$

For the Brovey transform, the 2, 3, 4 bands of Quickbird data were considered as the multispectral bands (i.e. Band1, Band2, Band3), while the panchromatic image was considered as the multiplying band (i.e. High Resolution Band).

Gram-Schmidt fusion method: The Gram-Schmidt process is a procedure that takes a nonorthogonal set of linearly independent functions and constructs an orthogonal basis over an arbitrary interval with respect to an arbitrary weighting function. In other words, this method creates from the correlated components non- or less correlated components by applying the orthogonalization process.

Generally, orthogonalization is important in diverse applications in mathematics and other applied sciences because it can often simplify calculations or calculations by making it possible, for example, to perform the calculation in a recursive manner [20].

Given an arbitrary basis $\{u_1, u_2, \dots, u_n\}$ for n-dimensional inner product space V, the Gram-Schmidt algorithm constructs an orthogonal $\{v_1, v_2, \dots, v_n\}$ for V and the process can be described as follows:

$$\begin{aligned} v_1 &= u_1, \\ v_2 = u_2 - project_{w1}, \quad u_2 &= u_2 - \frac{\langle u_2, v_1\rangle}{\|v_1\|^2} v_1, \\ v_3 = u_3 - project_{w2}, \quad u_3 &= u_3 - \frac{\langle u_3, v_1\rangle}{\|v_1\|^2} v_1 - \frac{\langle u_3, v_2\rangle}{\|v_2\|^2} v_2, \\ v_4 = u_4 - project_{w3}, \quad u_4 &= u_4 - \frac{\langle u_4, v_1\rangle}{\|v_1\|^2} v_1 - \frac{\langle u_4, v_2\rangle}{\|v_2\|^2} v_2 - \frac{\langle u_4, v_3\rangle}{\|v_3\|^2} v_3. \end{aligned}$$

where:
$w1$– space spanned by $v1$
$project_{w1}$ $u2$ is the orthogonal projection of $u2$ on $v1$
$w2$– space spanned by $v1$ and $v2$
$w3$– space spanned by $v1$, $v2$ and $v3$.

This process continues up to v_n. The resulting orthogonal set $\{v_1, v_2, \dots, v_n\}$ consists of n-linearly independent vectors in V and forms an orthogonal basis for V.

IHS transformation: It is defined by three separate orthogonal attributes, namely, intensity, hue, and saturation. Intensity represents the total energy or brightness of an image and defines the vertical axis of the cylinder. Hue is the dominant wavelength of the color inputs and defines the circumferential angle of the cylinder. Saturation is the purity of a color or the amount of white light in the image and defines the radius of the cylinder [21,22]. In the HIS each pixel is represented by a three-dimensional coordinate position within a color cube. The equations describing the transformation to the IHS can be written as follows:

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{Bmatrix} \frac{1}{\sqrt{3}} & \frac{\sqrt{2}}{\sqrt{3}} & 0 \\ -\frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & 1 \end{Bmatrix} \begin{Bmatrix} \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{Bmatrix} \begin{Bmatrix} R \\ G \\ B \end{Bmatrix},$$

$$\begin{aligned} I &= \frac{(x+y+z)}{I_m(H,S)}, \\ H &= \tan^{-1}\left[-\frac{\sqrt{z}}{\sqrt{x}}\right], \\ S &= \cos^{-1}\left[\frac{\sqrt{y}}{\sqrt{x+y+z}}\right] / K_m(H). \end{aligned}$$

where:
$I_m(H,S)$ – maximum intensity permitted at a given H and co-latitude
$K_m\,(H)$ – maximum co-latitude permitted at a given H.

To get a quality color image that can illustrate spectral and spatial variations of the available objects in the selected Quickbird image, different band combinations have been used. The applied methods created different images of varied qualities. The image created by the Brovey transform looked very much like the original multispectral image and did not show worthy color illustrations of the available land use classes. The result of the Gramme-Schmidt fusion method was better than that of the Brovey transformed image in terms of spatial separation of the classes.

However, this image did not illustrate a sufficient color separation among different types of land use. Unlike the images created by the Brovey transform and Gram-Schmidt fusion, the IHS transformed image gave a superior result in terms of both spectral and spatial separations between different objects and classes. Therefore, for the interpretation of the building class, the image created by the IHS transform has been used. Figure 1 shows an original Quickbird image and its comparison with other images obtained by different fusion methods.

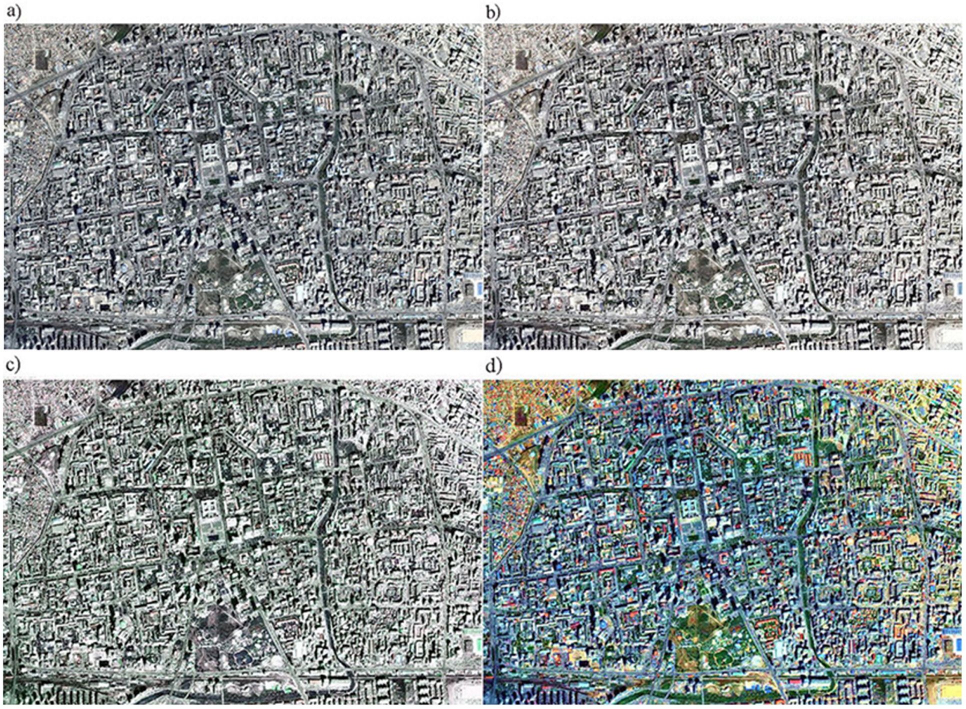

Figure 1: Original image (a); Fused images: Brovey transform (b), Gram-Schmidt method (c), IHS transformation (d).

4. The results

4.1. Creation of a Database and Land Use Change Analysis

In the study, we used topographic maps of the study that were georeferenced to a UTM map projection [1]. To create initial digital data, the buildings were screen-digitized from the georeferenced topographic maps of 2000 using ArcGIS system. After that for each building object, the attributes such as "area, polygon, use, built_year, storey, etc."were entered.

After creation of the database, it was necessary to update it, and for this purpose, the IHS transformed image of 2023 has been used. At first, the Quickbird image coordinates were transformed to the topographic map coordinates using 15 ground GCPs. For the transformation, a second-order transformation and nearest-neighbor resampling approach were applied and the related RMSE was 0.62 pixel. Then, on the georeferenced Quickbird image, the buildings were screen-digitized and updated the database of 2000. After that, for all new building entities, attributes such as “area, polygon, use, built year, story, etc.” were entered. The map indicating the old and updated information is shown in Figure 2.

Figure 2: The old (yellow) and updated (green) information of Ikh toiruu.

To analyze the changes that occurred before and after 1990, the ArcGIS system was used. After selecting the building entities for the selected time interval, a related number and their occupying areas were calculated. The comparison of the number of objects and total areas before and after the market economy is shown in Figure 3.

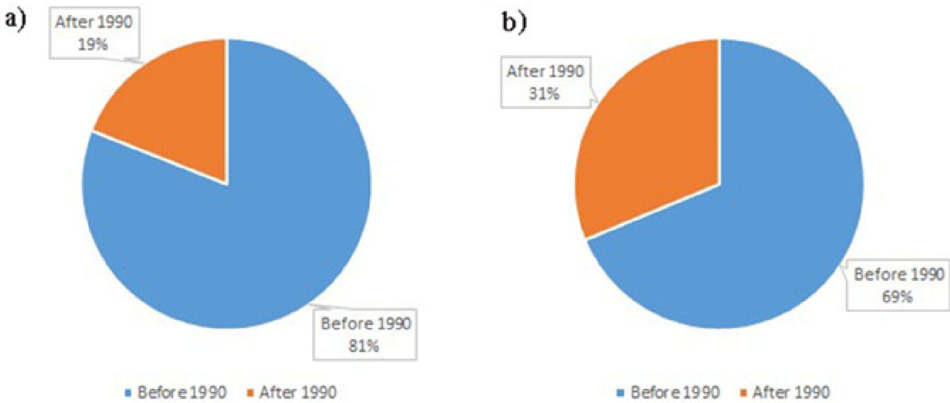

Figure 3: Comparison of the total number of buildings (a) and their occupying areas (b) in the Ikh toiruu before and after 1990.

As could be seen from the interpretation and related analysis, in the Ikh toiruu area, 628 buildings were built occupying 576,877 sq.m before 1990. However, after 1990 until the year 2023 2673 buildings have been built having 1,268,985 sq.m. The main reasons for these are as follows.

- Intensive construction of buildings in the study area commenced in the 1950s. However, until 1990, the Mongolian government built primarily large buildings with a few storeys occupying larger areas. Therefore, there are a few buildings.

- The rapid increase of the buildings after 1990 is due to the fact that the individuals desired to have lands in areas with good infrastructure and service, especially in closer to the CBD locations.
- From the early 1990s, business entities and private people began to replace the large buildings with own businesses and houses. Those newly contructed constructions usually occupied smaller areas.

3D views (from northeast direction) of the buildings placed on top of the IHS transformed image are shown in Figure 4. As seen from the figure, there were built mainly low-rise and middle-rise buildings before 1990. However, after the market economy, many high-rise buildings have been erected in the study area.

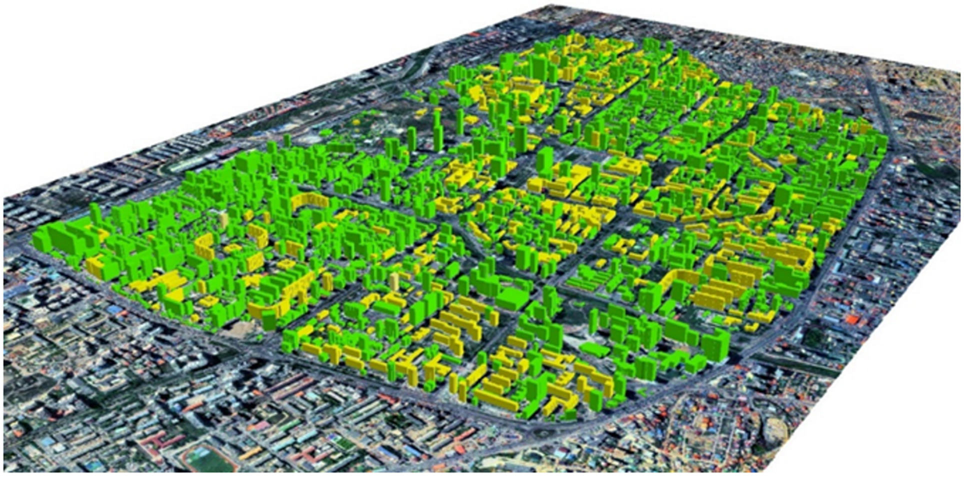

Figure 4: 3D view of the buildings in the Ikh toiruu before (yellow) and after (green) 1990.

5. Conclusions

The overall goal of the study was to analyze the urban land use changes in the Ikh toiruu area of the Mongolian capital city using very high resolution satellite images and some GIS dataset. For the study, the changes that occurred in Ulaanbaatar before 1990 were compared with the changes that occurred after 1990 and the reasons for the changes were described. For the initial creation of spatial and attribute databases, a topographic map of 2000 (scale of 1:5000) of the study area and description of the spatial entities were used. To update the created database, panchromatic and multichannel Quickbird images of 2023 were used. For the fusion, a Brovey transform, Gram-Schmidt method and IHS transformation were compared, and the best result demonstrated the HIS method. To extract the reliable land use information from the integrated RS image, a visual interpretation was applied. Overall, the research demonstrated that during the market economy the centre of Ulaanbaatar city was urbanized at a prompt rate. The main reasons were the facts that business entities and individual people wanted to have own properties in areas with good infrastructure and service, especially in locations closer to the city centre. Therefore, planning and management of the capital city might be reevaluated.

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Улаанбаатарын хотын газар ашиглалтын өөрчлөлтийг зайнаас тандах судлал ба ГМС ашиглан судалсан дүн

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Хураангуй: Сүүлийн жилүүдэд Монгол улсын нийслэл Улаанбаатарт хотжилт маш хурдацтай нэмэгдэж байна. Хотжилт тэлэх олон шалтгаан бий боловч гол шалтгаан нь амьдралын нөхцөлийг сайжруулахыг эрэлхийлж буй хөдөөгийн иргэдийн шилжилт хөдөлгөөнтэй холбоотой юм. Энэхүү судалгааны зорилго нь зайнаас тандах судлал (ЗТС) болон газарзүйн мэдээллийн систем (ГМС)-ийн өгөгдлийг ашиглан нийслэлийн төв хэсгийн газар ашиглалтын өөрчлөлтөд дүн шинжилгээ хийх юм. 1:5000 масштабтай байр зүйн зураг болон газар ашиглалтын элементүүдийн түүхэн өгөгдлүүдээр орон зайн мэдээллийн санг бүрдүүлэн судалгаанд ашигласан болно. Мэдээллийн санг шинэчилж хотын газрын ашиглалтын бодит мэдээллийг гарган авахын тулд Quickbird дагуулын 2023 оны хэт өндөр нарийвчлалтай панхроматик болон олон бүсчлэлийн зургуудыг нэгтгэн ашиглалаа. Дүрс мэдээг нэгтгэхдээ ангиудын орон зайн болон спектрийн тодролыг сайжруулах үүднээс Бровейн шилжүүлэлт, Грамм-Шмидтийн арга ба өнгө-эрчим-ханалт (IHS) хувиргалтын аргуудыг ашиглан үр дүнгүүдийг харьцуулсан. Эдгээр аргуудаас IHS-ийн хувиргалтын үр дүн нь өөр өөр объект болох ангиуд хоорондын спектрийн болон орон зайн хувьд хамгийн сайн ялгаж байсан тул цаашдын дүн шинжилгээнд сонгосон. Энэхүү судалгааны үр дүн нь Улаанбаатар хотын төв хэсэг хэт их нягтшилтай, нарийн төлөвлөлт хийх шаардлагатай байгааг харууллаа.

Түлхүүр үгс: Хотын газар ашиглалт, Зайнаас тандан судлал, дүрс мэдээг нэгтгэх, өөрчлөлтийн судалгаа