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Review / Pregledni znanstveni članak

Assessing the Potential of High-Resolution Satellite Imagery for Urban Expansion Analysis

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ABSTRACT. This paper addresses the practical need for urban area protection against unplanned and illegal construction, particularly individual housing units. The city of Sarajevo, Bosnia and Herzegovina, serves as a case study, where extensive unauthorized housing development occurred after the war in the 1990s. Change detection using remotely sensed imagery is primarily based on comparative analysis. A test area of 1 km² in the western part of Sarajevo was selected, where significant changes were observed by overlapping high-resolution IKONOS panchromatic satellite images from three different years (2001, 2004, and 2006). By analyzing the overlapping images, significant housing development in the area was revealed. This approach enables municipal and other relevant authorities to obtain accurate spatial and temporal data on new construction in specific regions.

Keywords: remote sensing, satellite image, IKONOS, change detection.

1. Introduction

Remote sensing techniques can provide geospatial data that track changes in land cover and land use over time (Gašparović et al. 2017). People are naturally adept at interpreting images because they do this constantly – even reading is a form of image analysis. Images provide us with spatial information

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about objects, including their location, size, and relationships to one another (Oštir and Mulahusić 2014, Kulo 2019). Rapid and precise assessments make remote sensing technologies valuable in various fields, such as monitoring changes in land cover (Ustuner and Sanli 2017, Tuno et al. 2017, Mulahusić et al. 2018a, Šandera and Stych 2019, Veljanovski et al. 2019, Lemenkova 2020, Sivac and Hrelja 2022, Marić and Smajo 2023), monitoring urban heat islands (Mulahusić et al. 2018b, Mulahusić et al. 2021), detection of illegal landfills (Krtalić et al. 2018, Kulo and Điđelija 2021, Điđelija et al. 2022), drought monitoring (Điđelija et al. 2023), detection of water bodies (Čotar et al. 2016), monitoring of land subsidence (Bojić 2023). Remote sensing also offers vast potential for applications in spatial planning and urbanism (Ciceli and Prosen 2003). Using multi-temporal satellite images and image processing techniques for automatic change detection is an effective approach to identifying illegal constructions in urban areas (Moghadam et al. 2015).

Illegal housing is a significant issue for the city of Sarajevo (Figure 1), Sarajevo Canton, and Bosnia and Herzegovina as a whole. The widespread illegal construction and urbanization threaten the quality of life, hinder effective spatial planning, and obstruct environmental management efforts (Mulahusić 2010). Thousands of these structures were constructed both before and after the Bosnian War (1992–1995) on the slopes and agricultural land surrounding Sarajevo's central areas. Estimates suggest that by 1986, the number of illegal housing units in Sarajevo approached 40,000. An additional 25,000 to 50,000 illegally constructed units were completed during the post-war period. A considerable number of single-family homes were built without construction permits, indicating the lack of essential infrastructure such as sewers, stormwater drainage, septic systems, water supply, or wastewater management. This results in unregulated flows, increasing the likelihood of landslides (Martín-Díaz et al. 2016). The primary cause of landslides in the Sarajevo Canton has been the widespread illegal construction of residential buildings (Serdarević and Babić 2019). The urban structure of these settlements consisted mainly of a series of individual single-family homes constructed on unstable land, lacking basic services, paved roads, educational facilities, and efficient public transportation (Aquilué and Roca 2016). Despite the presence of regulatory plans, the surplus of housing that surpasses the actual demand for living units, widespread illegal residential construction, experimentation with housing typologies, and the unappealing visual language of residential architecture have significantly harmed Sarajevo's living environment (Zejnilović and Husukić 2018). According to data presented by Čustović at al. (2015), illegal construction affects mostly the first agro-zone (the best quality land), which, under the current legislative framework, is treated as a zone of no construction.

Although the case study in this paper focuses on the western part of Sarajevo (specifically the Rajlovac suburb), many of its conclusions and principles can be applied to other cities as well. The aim of this study was to analyze data from the period between 2001 and 2006, which saw the highest levels of post-war illegal construction in Sarajevo. Using high-resolution satellite imagery and remote sensing technology, we are able to identify these changes, analyze their impact, and propose concrete actions to help authorities prevent the uncontrolled expansion of the city.

Figure 1. *Example of illegal residential buildings constructed in the Novi Grad municipality, Sarajevo (photo taken by Admir Mulahusić).*

2. Urban Areas and Change Detection

All dynamic changes driven by urbanization contribute to the rapid and continuous transformation of structures in urban areas. Traditional methods of data collection and change detection are often too slow to keep up with this pace. Interestingly, the European Union, as one of the most urbanized regions in the world, faces conflicts primarily related to land use planning and development. To address this, the EU Commission has initiated several studies, such as "Monitoring Urban Dynamics", which aims to promote the harmonious and balanced development of European landscapes (Steinnocher et al. 1999).

Satellite remote sensing is an ideal source of up-to-date information for urban planning. As the complexity of planning issues and the demands for data processing continue to grow, expectations regarding data performance – such as positional accuracy and data attribution –have also increased (Meinel et al. 1998). The use of satellite imagery for data collection across larger urban areas is crucial for city management, urban planners, town planners, urban sociologists, and others involved in the planning and implementation of urban decisions (Oštir and Mulahusić 2014). Urban areas are defined by factors such as location, population density, social and economic organization, and the transformation of natural, undeveloped environments into built-up areas (Rashed and Jürgens 2010).

It is estimated that half of the world's population currently lives in urban areas, and by the middle of the 21st century, two-thirds of people will reside in cities. This is striking, considering that in 1850, only 2% of the population lived in cities with over 100,000 inhabitants. By 1900, that number had risen to around 6%, and by 1950, it had reached 16%. Today, many cities around the world have populations exceeding 100,000, and such cities are now considered relatively small. The process of urbanization has significantly accelerated, particularly in economic and administrative centers. The number of "million cities" and "megacities" continues to grow, driving the expansion of urban sprawl (Cavrić and Keiner 2006).

In many countries, satellite imagery has become an essential and irreplaceable tool for monitoring urban areas. By comparing satellite images of the same location taken at different times, we can create a historical archive that provides insights into the growth and changes of urban areas over time. One key advantage of satellite imagery is that it allows for constant monitoring of a region, at any time, from any location. Satellite images offer an objective view of the so-called "zero state" – the condition of an area before any technical interventions or construction took place. This makes satellite imagery valuable as evidence of all changes over time. Moreover, satellite images are invaluable in urban planning and construction. They represent the most up-to-date topographic maps, providing a comprehensive view of the current situation on the ground and enabling the analysis of entire urban areas, not just specific sites.

Recent studies (Veljanovski et al. 2011, Malmir et al. 2015, Akin et al. 2015, Yildiz and Doker 2016, Wu et al. 2016) demonstrate the effectiveness of remote sensing data in detecting changes within urban areas. While the detection of illegal buildings has been less explored compared to general land use changes, several methods have been proposed for identifying unauthorized structures (Moghadam et al. 2015, Varol et al. 2019).

Change detection refers to the process of recognizing variations in the condition of an object or phenomenon through observations made at different time intervals (Singh 1989). The goal of change detection is to compare spatial representations of an area at two (or more) time points, while controlling for variations caused by factors that are not of interest, and to measure changes related to the variables of interest (Green et al. 1994). This often involves identifying "significant" changes and filtering out "insignificant" ones (Radke et al. 2005).

The core principle of using remote sensing data for change detection is that changes in the object of interest will result in variations in radiance values or local texture. These changes can be distinguished from those caused by other factors, such as variations in atmospheric conditions, lighting, viewing angles, or soil moisture (Mulahusić 2010). However, since change detection is influenced by spatial, spectral, thematic, and temporal constraints, and since many different techniques are available, selecting the appropriate methodology or algorithm for a specific project is crucial but not always straightforward.

According to Lu et al. (2004), change detection methods can be classified into seven categories: (1) algebraic methods, (2) transformations, (3) classification, (4) advanced models, (5) GIS-based approaches, (6) visual analysis, and (7) other methods. Each category varies in complexity. The seventh category includes techniques that do not fit into the other six and are not yet widely used in practice (Mulahusić and Tuno 2011).

3. Satellite Images and Study Area Overview

The selected study area is located in the western part of Sarajevo (Figure 2). An analysis of this area revealed that in the first decade of the 21st century, approximately 60% was covered by meadows and fields, over 25% by forests and orchards, 10% by road infrastructure, and 5% by buildings. Following initial assessments, a more detailed analysis of the area was conducted.

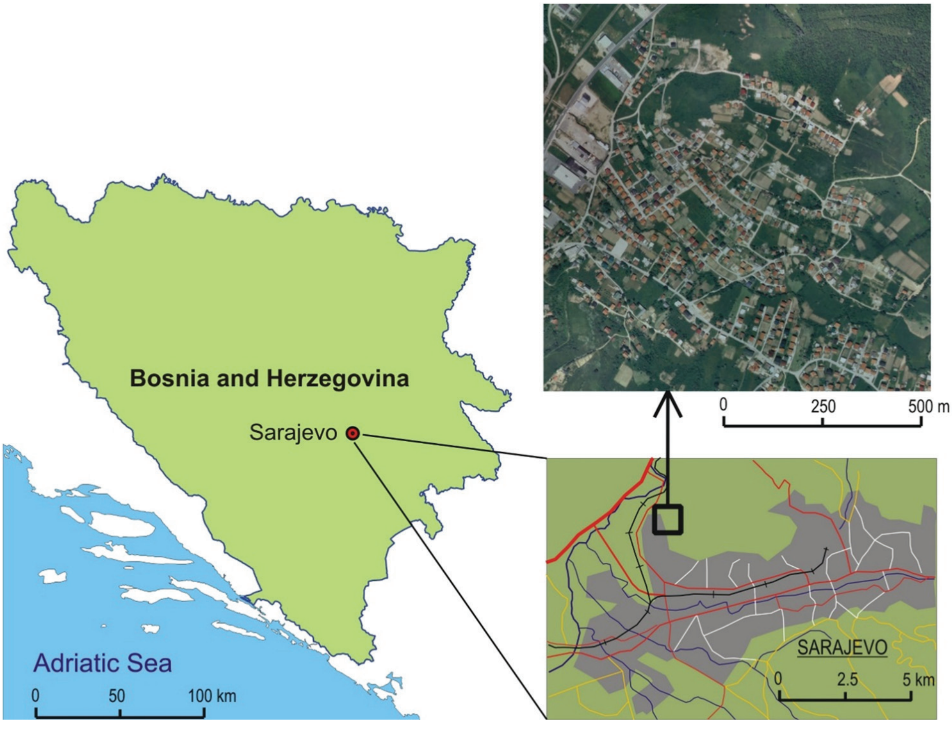

Figure 2. *Location of the test area.*

For the purpose of studying urban sprawl in Sarajevo, high-resolution panchromatic IKONOS satellite images from 2001, 2004, and 2006 were used (Figure 3 and 4). The IKONOS satellites were the first commercial satellites to offer publicly available high-resolution imagery with a spatial resolution of 1 meter. IKONOS provided a 1-meter spatial resolution for panchromatic images and a 4-meter resolution for multispectral images. More recent satellite generations, such as WorldView and QuickBird, offer even better spatial resolution, often at 1 meter or higher. Additionally, radiometric resolution has significantly improved compared to earlier satellites, allowing for more detailed identification of features from satellite imagery – an advantage that is crucial for urban planning (Bolt 1996).

4. Analysis and Interpretation of Images

Visual analysis and interpretation of satellite imagery involve the registration and identification of relevant data using the sense of sight. Humans interact with their environment primarily through vision, with the brain processing and analyzing the content of the images it perceives.

When visually analyzing satellite images, specific criteria are applied to facilitate the identification of objects and phenomena. These criteria include spectral values, color, size, texture, shape, position, contrast with surrounding features, shadows, and structure.

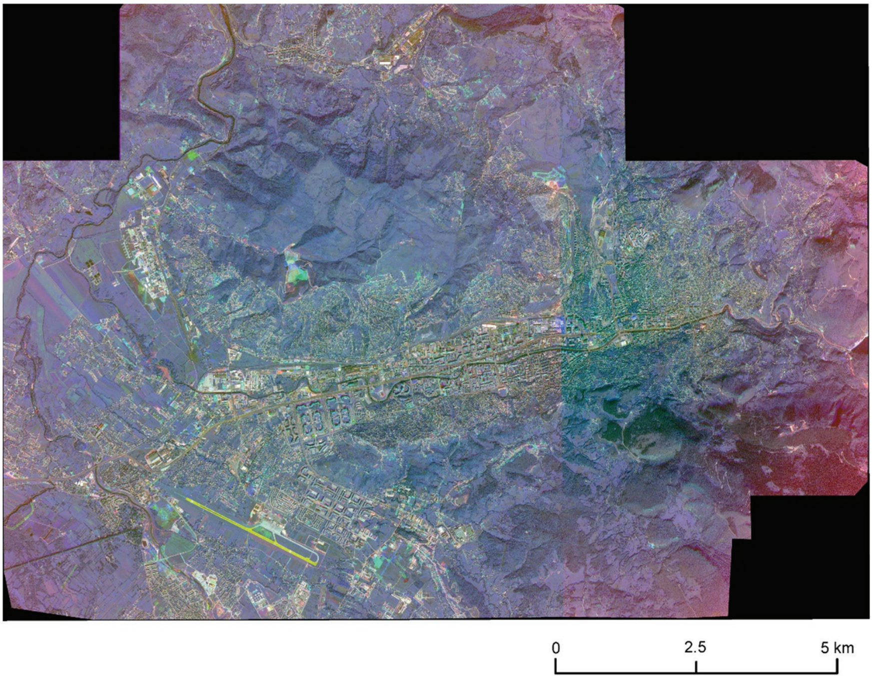

Figure 3. *Urban area of Sarajevo: result of overlapping panchromatic images from 2001, 2004, and 2006.*

One of the most critical factors in image analysis is the contrast, which refers to the difference between the brightest and darkest tones in an image. Other important considerations include understanding the spectral bands, resolution, and sensor characteristics. Knowledge of the image processing techniques used and the reflectance properties of different objects across various spectral ranges is also essential for accurate interpretation. All these factors are crucial for correctly interpreting satellite imagery.

Computer-aided image analysis is employed for more detailed processing, enabling the identification and extraction of specific data that may not be detectable through visual analysis alone. The analysis and interpretation of satellite images can be broadly divided into two categories: visual analysis and interpretation, and computer-assisted analysis and interpretation. For both types of analysis, the resolution of the satellite image plays a key role in ensuring accuracy and reliability (Mulahusić 2010).

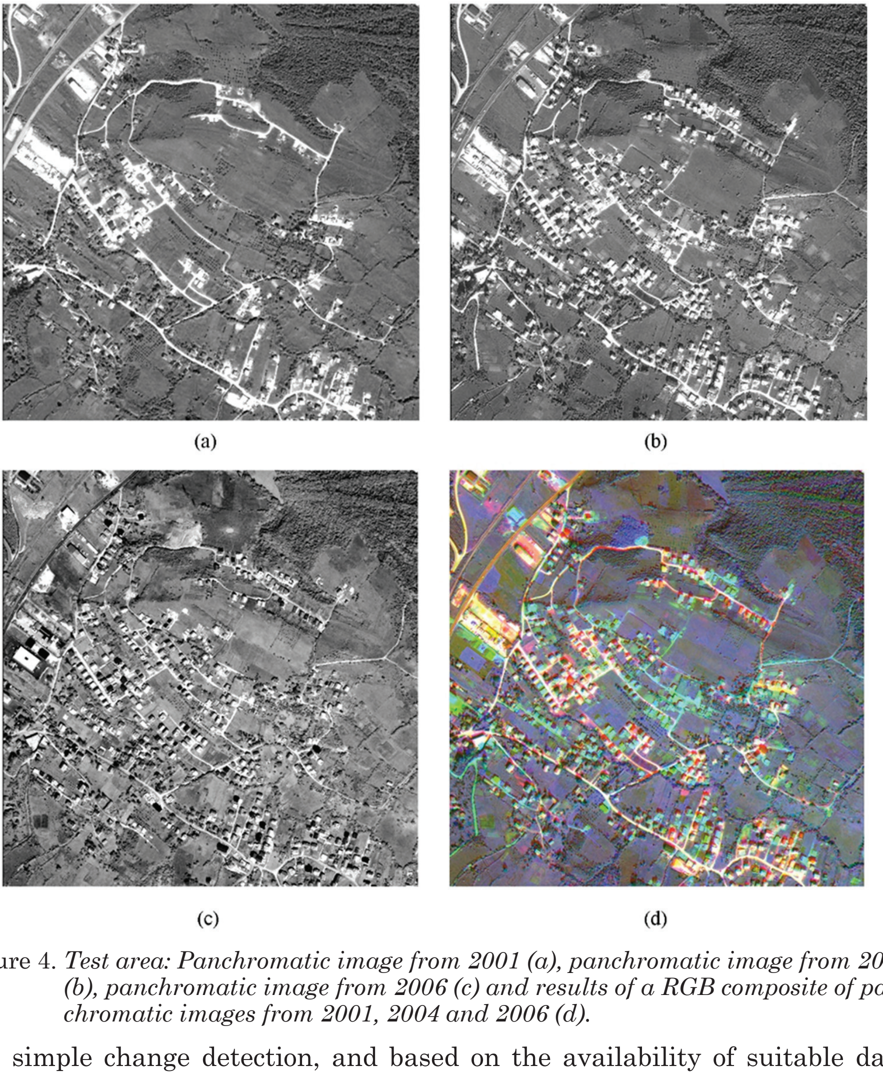

Figure 4. *Test area: Panchromatic image from 2001 (a), panchromatic image from 2004 (b), panchromatic image from 2006 (c) and results of a RGB composite of panchromatic images from 2001, 2004 and 2006 (d).*

For simple change detection, and based on the availability of suitable data sources (panchromatic satellite images from 2001, 2004, and 2006), the approach involved overlapping the panchromatic images to detect changes that occurred during the relevant periods. To facilitate change detection, each panchromatic image was assigned to one of the RGB color bands, creating a composite image. Specifically, the panchromatic image from 2001 was assigned to the red band, the panchromatic image from 2004 to the green band, and the panchromatic image from 2006 to the blue band, resulting in a composite image (Figure 3 and 4). As shown in Figure 3 and 4, the image contains not only gray shades but also other colors, which highlight the changes that occurred during the specified time periods. While visual analysis of this image could be complex, a decision was made to use green as the color to represent all visible changes, making it easier to identify alterations over time.

One of the options available is the NDVI (Normalized Difference Vegetation Index). The practical application of this method is detailed by Mulahusić (2010). NDVI has long been used as an effective tool for assessing biomass in a given area (Rumora et al. 2016, Pilaš et al. 2019). However, one of its main drawbacks is the difficulty in interpreting changes in the resulting image. While the method is commonly used to detect changes in vegetation, it has also proven useful for identifying changes in the growth of urban areas, which represents a novel application.

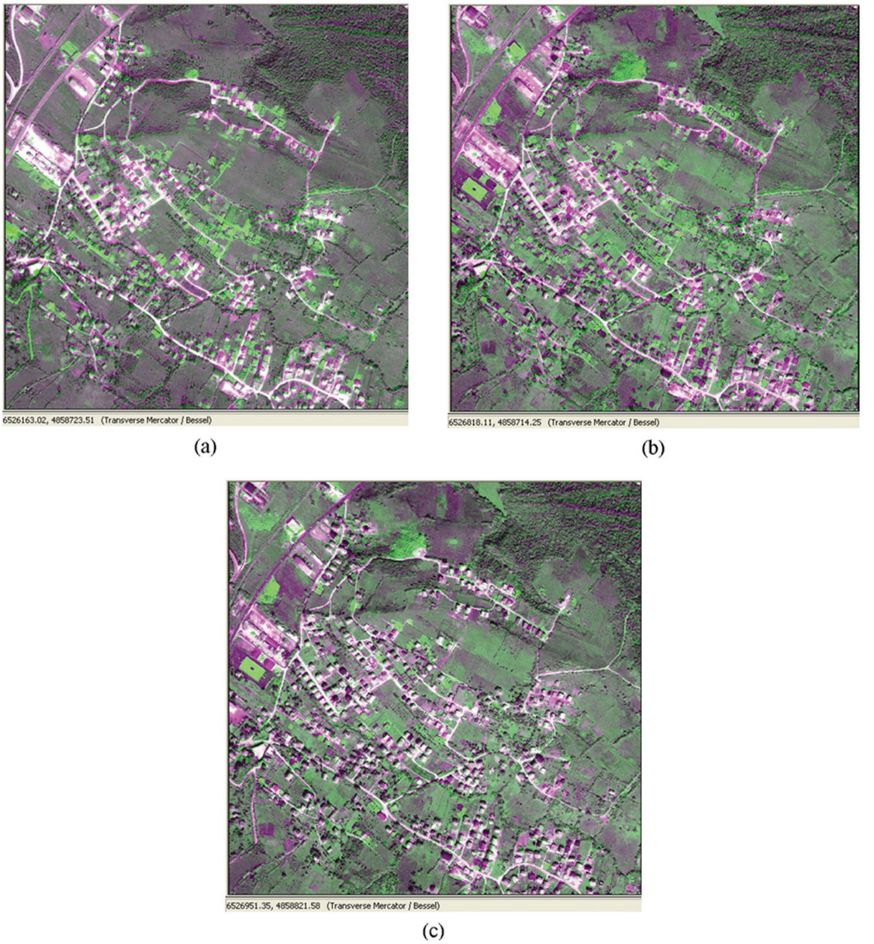

Figure 5. *Test area: Changes in the period from 2001 to 2004 (a), changes in the period from 2001 to 2006 (b), changes in the period from 2004 to 2006 (c). The changes are in green.*

One of the key advantages of the NDVI method, as highlighted by Mulahusić (2010) is its speed, due to the relatively small size of the panchromatic data files. This method allows for monitoring changes across four different time periods, provided we can use a false Digital Elevation Model (DEM) to represent the fourth period. By adjusting the RGB values, it is possible to highlight corresponding changes during specific periods. For example, by selecting the values 1, 1, 1, we generate an image from 2001; selecting 2, 2, 2 produces an image from 2004; and selecting 3, 3, 3 results in an image from 2006. In Figure 3, the option 1, 2, 3 is selected, showing all three images and the changes that occurred between 2001 and 2006.

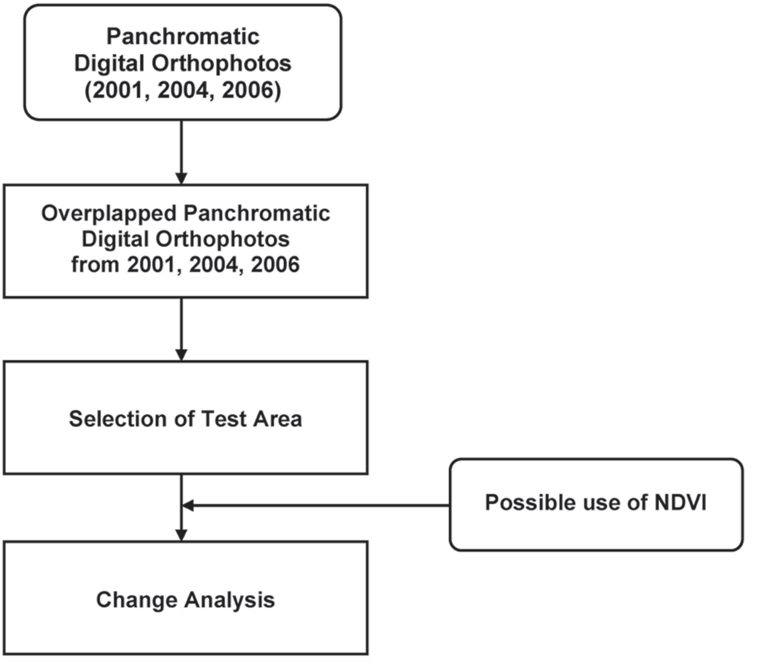

Figure 6. *Analysis of panchromatic satellite images.*

After extensive practical testing, it was concluded that green is the most suitable color for detecting changes. Based on this conclusion, Table 1 presents the options for detecting changes during specific time periods, using green to highlight the variations.

Notably, significant changes in individual housing construction were identified within the test area. By adjusting the RGB values for the test area, it is possible to highlight the corresponding changes in the relevant time periods (2001–2004, 2001–2006, 2004–2006). The results of these overlapped panchromatic images are shown in Figure 5a, 5b, and 5c. Figure 6 illustrates the possible analysis process for panchromatic digital orthophotos.

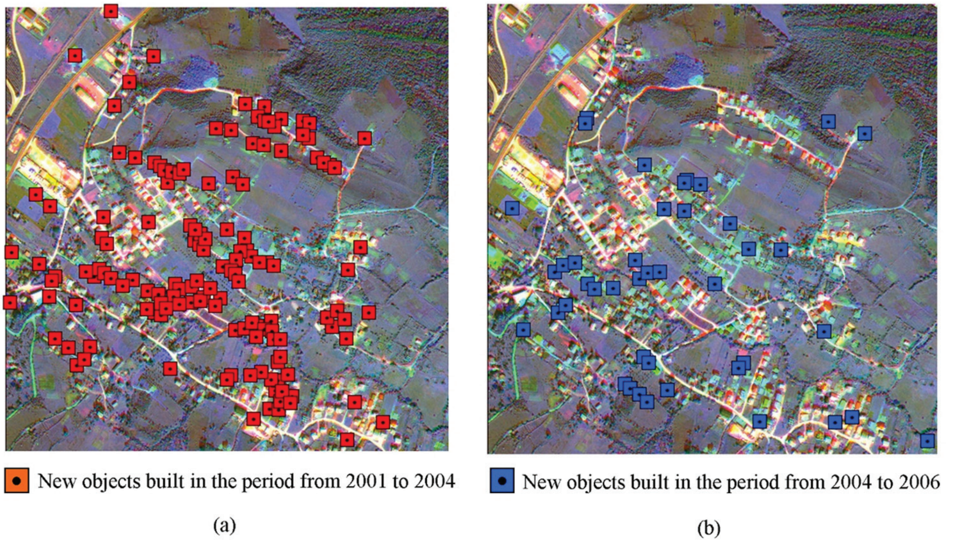

Figure 7. *Test Area: Locations of new buildings constructed between 2001 and 2004 (a), and locations of new buildings constructed between 2004 and 2006 (b).*

In addition to changes in individual housing construction, substantial alterations were observed in road infrastructure, which evidently developed alongside the housing expansion. Minor changes were noted in agricultural land use, where areas used for agricultural activities in 2001 remained in use for the same purpose in both 2004 and 2006. As previously mentioned, the primary focus of the change analysis was on individual housing units.

Table 1. *Alternative band combinations for detecting changes (in green) across different time periods.*

Band selection options	**The period when the change occurred**
1, 2, 1	2001 – 2004
1, 3, 1	2001 – 2006
2, 3, 2	2004 – 2006

Based on the analysis of overlapped panchromatic satellite images from 2001, 2004, and 2006, the following findings were made:

- Between 2001 and 2004, 141 new buildings were constructed in the 1-square-kilometer test area (Figure 7a).
- Between 2004 and 2006, 42 new buildings were constructed in the same test area (Figure 7b).

The validation of the obtained results was conducted through a field investigation, where all identified new houses were confirmed through on-site inspection.

5. Conclusion

This research was motivated by the need to protect urban areas threatened by unplanned and illegal construction, particularly individual housing units. Similar studies have been conducted in other developing countries facing the same issues as Bosnia and Herzegovina, which have struggled to address illegal construction effectively. As urban planning and land management require accurate, up-to-date data, this study aimed to identify indicators that could quickly provide authorities with spatial and temporal data on new construction. The goal was to develop a simple method that provides an accessible approach for individuals without specialized knowledge in advanced satellite imagery analysis, such as municipal urban planning employees, allowing them to effectively detect illegal housing.

The analysis revealed significant housing growth in the test area, with 141 new buildings constructed between 2001 and 2004, and 42 more between 2004 and 2006. During the analysis, it was possible to determine whether a building was under construction or completed. Unfinished buildings were often identified by strong reflections, indicating asphalt surfaces, while construction sites showed small shadows beside the structures. Some ambiguity arose when residential roofs were replaced, which could lead to misinterpretation, highlighting the need for caution in analysis.

This study demonstrates the potential of using high-resolution IKONOS satellite images for urban planning and change detection. While higher-resolution satellite imagery would yield better results, IKONOS images offer a cost-effective solution for monitoring urban development. While the test area is relatively small, it is believed that the findings of this study can be broadly applied to other cities with characteristics similar to Sarajevo. Advanced image analysis techniques, such as machine learning, could enhance accuracy and automation, and they can be applied in future research.

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Ispitivanje potencijala satelitskih snimaka visoke rezolucije za analizu urbanog širenja

SAŽETAK. U radu se govori o praktičnoj potrebi zaštite urbanog područja od neplanske i bespravne gradnje, posebno individualnih stambenih objekata. Grad Sarajevo, Bosna i Hercegovina, poslužio je kao studija slučaja, gdje je došlo do opsežne nelegalne stambene izgradnje nakon rata 1990-ih. Otkrivanje promjena pomoću snimaka daljinskih istraživanja prvenstveno se temelji na komparativnoj analizi. Odabrano je testno područje od 1 km² u zapadnom dijelu Sarajeva, gdje su uočene značajne promjene preklapanjem IKONOS pankromatskih satelitskih snimaka visoke rezolucije iz tri različite godine (2001., 2004. i 2006.). Analiza preklopljenih snimaka otkrila je značajnu stambenu izgradnju u tom području. Ovaj pristup omogućuje općinskim i drugim nadležnim tijelima dobivanje točnih prostornih i vremenskih podataka o novogradnji u određenim regijama.

Ključne riječi: daljinska istraživanja, satelitske snimke, IKONOS, utvrđivanje promjena.

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