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Research Article

Enhancing Land Monitoring Methods for Rural Settlements: A Digital Lock Approach

Yuliya Romanyuk

Associate Professor, Department of Engineering Geomatics, Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan

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Abstract

This paper presents the results of research on improving land monitoring methods for rural settlements, based on a case study of the "Abay" mahalla in the Kuyi Chirchik district of Tashkent region, Uzbekistan. Traditional monitoring methods demonstrate reliability of only 70-85%, which is insufficient for timely detection of land grabs and unauthorized conversion of agricultural land. The study proposes an integrated approach combining retrospective analysis of satellite imagery (Google Earth Pro, 2002-2025), UAV-based aerial photography (DJI Phantom 4 Pro Plus, 0.05 m resolution), GNSS surveying (Stonex S6II, ±5 mm accuracy), and blockchain-based cryptographic fixation of results. The developed "Digital Lock" algorithm provides six levels of data protection, ensuring legally irrefutable documentation of land boundaries and usage. Implementation on an 86-hectare site reduced field survey time from 14 days to 1.5 hours, increased data reliability from 70-85% to 99%, and reduced labor costs by 88%. For the study area, a Soil Sealing Coefficient of 39.7% was established, indicating critical loss of irrigated arable land. The method is recommended for replication in suburban areas of Uzbekistan's regional centers to support general planning of rural settlements and implementation of the "Obod Kishlok" program.

Keywords: land monitoring, rural settlements, UAV, GNSS, blockchain, soil sealing coefficient, Digital Lock, Tashkent region.

1. INTRODUCTION

Rapid urbanization is exerting increasing pressure on rural territories globally. According to UN data, by 2050, the area of land occupied by rural settlements will increase by at least 30%, primarily at the expense of irrigated agricultural land – the most valuable resource [1]. The FAO report "The State of Food and Agriculture – 2025" states that annual losses of arable land to development globally are estimated at 1.5–2.0 million hectares, with the majority occurring in rural settlements where effective monitoring and control systems are absent [2].

In the Republic of Uzbekistan, annual losses of irrigated land to development amount to thousands of hectares. Traditional monitoring methods, with reliability not exceeding 85%, fail to timely identify land grabs and misuse of land. The absence of a unified digital platform and detailed classification of rural settlement lands makes the development of new monitoring methods a pressing priority [3].

This research aligns with the priorities of state land policy as defined in Presidential Decrees and Resolutions of the Cabinet of Ministers of the Republic of Uzbekistan, including Decree No. UP-5623 of January 10, 2019, "On measures to radically improve urbanization processes," Decree No. UP-5853 of October 23, 2019, "On approval of the agricultural development strategy of the Republic of Uzbekistan for 2020-2030," and Resolution No. 111 of March 4, 2024, "On the development of land management schemes for agricultural regions for 2025-2030" [4].

The aim of this research is to develop innovative methods for improving land monitoring in rural settlements, using the Tashkent region as a case study, and to support sustainable regional development.

2. METHODS

2.1 Study Area

The research was conducted in the "Abay" mahalla (rural settlement), which is part of the Kuyi Chirchik district of Tashkent region. The settlement covers an area of 86 hectares and is characterized by typical rural land use patterns: residential buildings, household plots (66.7% of the total area), engineering infrastructure, and agricultural lands. The population of the mahalla is 4,143 people (as of January 1, 2026).

2.2 Research Methods

The study employed the following methods:

analysis of land records, monitoring, and land management documentation;

topographic and geodetic field surveys;

remote sensing using satellite imagery and UAVs;

cartographic analysis and geovisualization;

statistical processing (approximation, regression analysis, correlation).

2.3 Integrated Monitoring Methodology

The developed "Digital Lock" algorithm comprises six sequential levels (fig. 1):

Level 1: Retrospective Analysis (Google Earth Pro). Satellite imagery for the period 2002-2025 (resolution 0.5-1 m) was analyzed to establish baseline land use and identify historical changes [5].

Level 2: UAV Survey. Aerial photography was conducted using a DJI Phantom 4 Pro Plus quadcopter (camera 4K, flight altitude 100 m, speed 15 m/s, image overlap 70%). Flight planning was performed in DJI Pilot software. According to the State Scientific and Design Institute "Uzdavyerloyikha," drone-based monitoring is being actively implemented in Uzbekistan's agricultural monitoring system [6].

Level 3: GNSS Ground Control. Surveying of control points (power line poles, building corners) was performed using a Stonex S6II GNSS receiver (accuracy: ±5 mm + 0.5 mm/km RMS in plan, ±10 mm + 0.5 mm/km RMS in height).

Level 4: Photogrammetric Processing. Data were processed in Agisoft Metashape Professional following the workflow: image alignment → dense point cloud generation → polygon model construction → texture creation → 3D model building → orthophotomap generation (0.05 m resolution) [7].

Level 5: Raster Calibration and Vectorization. Orthophotomaps were calibrated in NanoCAD using 18 control points (21 points/km^2 density) with the Bilinear method, achieving RMSE of 0.07 m [8]. Vectorization and semantic analysis were performed in AutoCAD/ArcGIS using the improved land classification with 9 territorial zones.

Level 6: Cryptographic Fixation. SHA-256 hash of the resulting topographic plan was computed and recorded in a distributed ledger (blockchain), ensuring legal irrefutability of the monitoring results. Research on blockchain and Earth Observation integration demonstrates the potential of combining satellite data with distributed ledger technologies for land administration and monitoring of land use compliance [9].

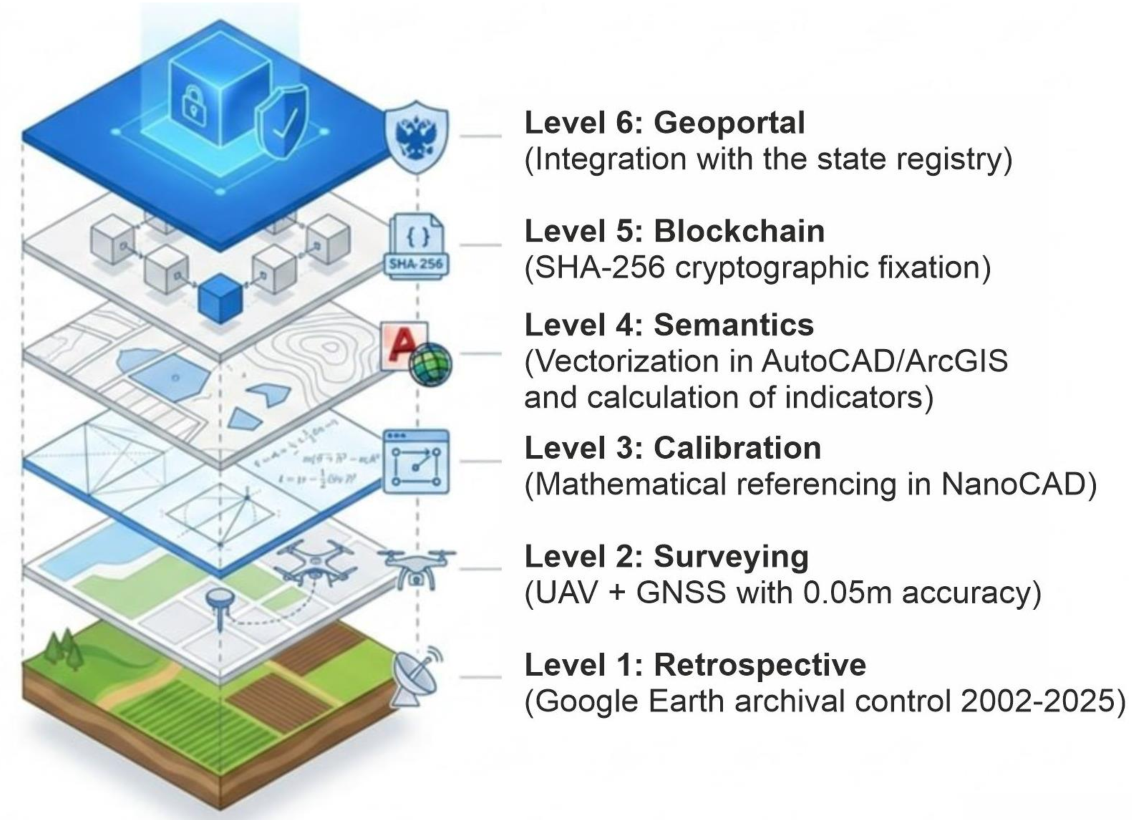

Fig. 1. Technological scheme of the "Digital Lock" framework for improving land monitoring in rural settlements

2.4 Soil Sealing Coefficient (SSC)

The Soil Sealing Coefficient was developed as a quantitative indicator of irreversible loss of agricultural land:

$$SSC = \frac{S_{sealed}}{S_{total}} * 100\%$$

where:

Ssealed – total land area occupied by foundations, impervious surfaces, roads, and other sealed surfaces (ha);

Stotal – total area of rural settlements within the monitoring boundaries (ha).

2.5 Construction Intensity Index (CII)

The Construction Intensity Index was developed to assess the dynamics of agricultural land withdrawal:

$$CII = \frac{\Delta S_{residential}}{\Delta S_{withdrawn}}$$

where:

$\Delta S_{residential}$ – the increase in residential land area (ha) over the period;

$\Delta S_{withdrawn}$ – the area of newly withdrawn agricultural land (ha).

3. RESULTS

3.1 Comparative Analysis of Survey Methods

Table 1 presents a comparative analysis of different survey methods for the 86-hectare "Abay" mahalla.

Table 1.
Comparative Analysis of Survey Methods for Rural Settlement "Abay"

Indicator	Traditional Method (Total Station)	GPS Survey	Google Earth	**Recommended Method ("Digital Lock")**
Field survey time (86 ha)	14 days	4 days	0 (no field work)	**1.5 hours**

Data processing time	16 hours	2 days	8 hours	**6 hours**
Labor costs	7.2 million sum	1.1 million sum	700 thousand sum	**850 thousand sum**
Data reliability	70-85%	85-90%	90-95%	**99%**
Orthophotomap resolution	1-3 cm (point)	—	0.5-1 m	**0.05 m**
Accuracy (RMSE per 1 ha)	0.5-1.0 m	0.005-0.01 m	0.5-1 m	**0.07-0.20 m**
Legal protection of results	No	No	No	**Yes (blockchain SHA-256)**
Retrospective analysis	No	No	Yes (from 2002)	**Yes (from 2002)**

The developed method exceeds each traditional approach in all key parameters: accuracy, timeliness, reliability, and legal protection. Field survey time was reduced by a factor of 224 (from 14 days to 1.5 hours), data reliability increased from 70-85% to 99%, and labor costs decreased by 88%.

3.2 Land Classification Improvement

The existing classification of rural settlement lands was improved by transitioning from 5 aggregated zones to 9 detailed territorial zones [10]:

1. Residential areas
2. Household plots
3. Public and business areas
4. Industrial areas
5. Engineering and transport infrastructure
6. Recreational areas
7. Specially protected areas
8. Water fund lands
9. Cemeteries

For the first time in Uzbekistan's monitoring practice, household plots, engineering infrastructure lands, and cemeteries were identified as separate categories, providing methodological basis for accurate land balance calculation.

3.3 Land Balance of "Abay" Mahalla

Based on the improved classification, a detailed land balance was compiled (Table 2).

Table 2.
Land Balance of "Abay" Mahalla

No.	Territorial Zone	Area, ha
1	Residential areas	7.99
2	Household plots	57.39
3	Public and business areas	4.41
4	Industrial areas	1.58
5	Engineering and transport infrastructure	11.32
6	Recreational areas	1.29
7	Water fund lands	2.04
	Total	**86.01**

Analysis revealed significant structural imbalances: household plots account for 66.7% of the total area, while residential areas account for only 9.3%. Recreational areas (1.5%) are deficient compared to the standard of 8-10 m^2/person, with an actual area of only 0.3 m^2/person.

3.4 Soil Sealing Coefficient (SSC) and Construction Intensity Index (KIT) Validation

For the "Abay" mahalla, the Soil Sealing Coefficient was calculated:

SSC =34.186.0×100%=39.7%

This corresponds to a high level of soil sealing (30-50% range), indicating that 34.1 hectares of irrigated arable land have been irreversibly lost to agricultural production.

The Construction Intensity Index was calculated considering official land transfers:

$CII_{official}$=7.9910.2=0.78

This exceeds the standard value of 0.3 by a factor of 2.6, indicating critically low efficiency of agricultural land use.

When including identified land grabs (24.66 ha) in the calculation:

CII_{actual}=7.9934.1=0.23

This falls within the standard range (≤0.3), confirming that housing deficits can be addressed through existing built-up areas without new agricultural land withdrawal.

3.5 Verification of Cadastral Data

Verification of cadastral data for nine land plots in the "Abay" mahalla revealed systematic discrepancies. Research by Papaskiri et al. [11] emphasizes that digital land management requires data obtained by replacing traditional methods with new technologies, including UAVs and high-resolution satellite images, to ensure information reliability.

Table 3.
Discrepancies in Land Area Data for "Abay" Mahalla

Experi-mental Plot	Google Earth Pro (m^2)	Agisoft Metashape (m^2)	GNSS (m^2)	Recommended Method (m^2)	Cadastral Agency Data (m^2)	Discrepancy (± m^2)
1	1,930.59	1,920.8	1,918.75	1,919.8	5,280	+3,360.2
2	1,511.54	1,509.9	1,507.00	1,508.0	1,450	-58.0
3	1,850.76	1,850.4	1,850.98	1,850.6	1,818	-32.6
4	1,941.25	1,945.7	1,945.84	1,945.8	1,824	-121.8
5	11,467.08	11,476.3	11,476.64	11,476.4	10,921	-555.4
6	2,015.72	2,000.1	1,999.98	2,000.0	1,570	-430.0
7	1,328.14	1,350.9	1,350.33	1,350.6	1,220	-130.6
8	1,301.38	1,291.0	1,291.26	1,291.1	1,315	+23.9
"Abay" Mahalla	858,830.0	860,130.3	860,130.56	860,130.4	307,516	-552,614.4

For Plot No. 1, the cadastral area (5,280 m^2) exceeds the actual area (1,919.8 m^2) by 3,360.2 m^2 (2.75 times). The total discrepancy for the mahalla is -552,614.4 m^2 (cadastre 307,516 m^2 versus actual 860,130.4 m^2), indicating systemic cadastral accounting errors requiring mandatory verification before blockchain fixation.

These findings align with the research by Abrham et al. [12], who demonstrated that semi-automated techniques using UAV imagery can significantly improve cadastral boundary extraction, especially in rural settings.

3.6 Economic Efficiency Assessment

The integrated annual economic effect of implementing the improved monitoring method is presented in Table 4.

Table 4.
Integrated Economic Effect of the Improved Monitoring Method

Effect Item	"Abay" Mahalla (86 ha)	Kuyi Chirchik District (32 SNPs)	Tashkent Region (830 SNPs)
Labor cost savings at monitoring	6.35 million sum (88%)	203 million sum/year	5.2 billion sum/year
Prevented damage from arable land preservation	1,364-2,387 million sum/year	2-5.6 billion sum/year	52-140 billion sum/year

Additional tax revenues from land grab legalization	15-25 million sum/year	0.5-0.8 billion sum/year	13-21 billion sum/year
Reduction in litigation costs	10-15 million sum/year	0.3–0.5 billion sum/year	8–13 billion sum/year
Integrated Annual Effect	**1,395-2,427 million sum**	**3-7 billion sum**	**78-179 billion sum**

The payback period for capital investment in equipping one district (UAV, GNSS, software – approximately 280 million sum) is less than 1.5 months.

4. DISCUSSION

4.1 Comparison with Existing Approaches

The developed method addresses the key limitations of traditional land monitoring in Uzbekistan. Existing approaches rely on fragmented data collection with 3-5 year intervals, reliability of 70-85%, and absence of legal guarantees for data integrity [13]. The proposed "Digital Lock" algorithm integrates:

1. **Retrospective analysis** (Google Earth Pro, 2002-2025) enabling detection of historical land use changes
2. **High-resolution UAV survey** (0.05 m) providing detail sufficient for legal boundary determination
3. **GNSS ground control** (accuracy ±5 mm) ensuring metrological traceability
4. **Blockchain fixation** providing legal irrefutability of results

The combination of these technologies creates a qualitatively new level of monitoring that not only identifies but also legally confirms land grab and unauthorized conversion of agricultural land.

4.2 Soil Sealing and Agricultural Land Protection

The Soil Sealing Coefficient (SSC = 39.7%) established for "Abay" mahalla indicates severe agricultural land loss. According to FAO data, land degradation assessment remains a critical challenge for sustainable agriculture [14]. The proposed SSC scale (≤10% - low, 10-30% - moderate, 30-50% - high, >50% - critical) provides a management tool for land use planning and risk assessment.

The Construction Intensity Index (CII) reveals that when land grabs are included, the actual CII (0.23) is within the standard range (≤0.3), while official transfers alone show critical values (0.78). This confirms that legalization of existing land grabs combined with densification of built-up areas can resolve housing deficits without new agricultural land withdrawal.

4.3 Blockchain for Legal Certainty

The use of SHA-256 hash recording in a distributed ledger represents a novel approach in land monitoring practice in Uzbekistan. According to the ESA white paper on Blockchain and Earth Observation, blockchain technology can significantly improve the accessibility, transparency, security, and traceability of information necessary for land administration and monitoring of land use compliance [9]. This ensures:

data immutability: any subsequent change to the topographic plan changes the hash;

temporal verification: survey time is cryptographically confirmed;

audit trail: authorized bodies can verify data authenticity at any time.

The legal mechanism for using blockchain fixation in state land control includes: comparison of actual boundaries with hashed data during inspections; using the hash as independent evidence in court proceedings; and enabling judicial verification through the Public Geoportal API.

4.4 Limitations and Future Research

While the method has proven effective on the pilot site, several challenges remain for scaling:

need for regulatory framework establishing mandatory blockchain fixation for cadastral work;

capacity building for land surveyors in UAV operation and blockchain technology;

development of API integration between the Public Geoportal and blockchain networks;

Addressing privacy concerns related to public blockchain data.

Future research should focus on: (a) automating SSC and CII calculation through machine learning algorithms applied to orthophotomaps, (b) expanding the method to non-irrigated agricultural lands, and (c) developing a mobile application for real-time land use change detection by mahalla committees.

5. CONCLUSION

The study presents a comprehensive methodology for improving land monitoring in rural settlements, addressing critical shortcomings of traditional approaches. The key achievements are:

1. **Improved land classification**: Transition from 5 aggregated zones to 9 detailed territorial zones, with household plots, engineering infrastructure, and cemeteries identified as separate categories for the first time in Uzbekistan's monitoring practice.
2. **Developed "Digital Lock" algorithm**: A six-level monitoring method providing data reliability of 99%, field survey time reduction by a factor of 224, and legal irrefutability through SHA-256 blockchain fixation.
3. **Introduced quantitative land protection coefficients**: SSC (Soil Sealing Coefficient) for measuring irreversible loss of irrigated arable land, and CII (Construction Intensity Index) for monitoring land withdrawal dynamics. For "Abay" mahalla, KZP = 39.7% (critical level), and CII decreases from 0.78 to 0.23 when including identified land grabs.
4. **Verified cadastral data**: Systematic discrepancies were identified (plot No. 1 discrepancy +3,360.2 m^2; mahalla total -552,614.4 m^2), proving the necessity of area verification before blockchain fixation.
5. **Demonstrated economic efficiency**: Labor cost savings of 88%, payback period of capital investment less than 1.5 months, and integrated annual effect for Tashkent region of 78-179 billion sum.
6. **Developed detailed land balance**: For "Abay" mahalla, revealing structural imbalances and identifying potential for densification without new agricultural land withdrawal.

The "Digital Lock" method is recommended for replication in all suburban areas of Uzbekistan's regional centers, supporting general planning of rural settlements for 2025-2030, implementation of the "Obod Kishlok" program, and the digital transformation of land control. Within 3-5 years, this approach can reduce annual irrigated arable land losses by 35-40% and create a digital register of household plots with cryptographic protection of boundaries and areas.

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