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HIGH-RESOLUTION REMOTE SENSING UNMASKS QANATS IN GOBUSTAN

Khabarova O.V.[1]*, Eppelbaum L.V.[2,3]

[1]*Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg*
29, Avenue J.F.Kennedy, Luxembourg, L-1855
[2]*Department of Geophysics, Tel Aviv University, Israel*
Ramat Aviv 6997801, Tel Aviv
[3]*Azerbaijan State Oil and Industry University, Azerbaijan*
20, Azadlig Ave., Baku, AZ1010
**Corresponding author: olga.khabarova@uni.lu*

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Summary. Recent studies demonstrate the effectiveness of integrated archaeo-geophysical tools in addressing a wide range of geological and environmental challenges. This approach combines geophysical methods with archaeological fieldwork or remote sensing to support the preliminary survey and analysis of archaeological sites, potentially enhanced by machine learning techniques to estimate the shapes and characteristics of subsurface objects. The present study emphasises the value of informational and probabilistic approaches as optimal tools for assessing and integrating critical data for archaeological research. We employ remote sensing to locate archaeological objects in the Gobustan region of Azerbaijan, which was inscribed on the UNESCO World Heritage List in 2007, and we demonstrate the substantial potential of combined archaeo-geophysical analyses to identify different categories of historical features in this area. For the analysis of freely accessible remote sensing data from different years and missions, advanced interpretation methodologies were applied. We have identified a sophisticated irrigation system characteristic of the Achaemenid Empire period extending beyond the Gobustan National Reserve, comprising interconnected canals, artificial lakes, and ponds, and associated with nearby settlements. The ancient qanats (kehrizes) easily recognisable in satellite images are among the most compelling discoveries, which have not previously been documented in this area. The next stage of this investigation will involve applying surface (or low-altitude) magnetic field analyses, including qualitative and quantitative interpretations of anomalies and three-dimensional modeling. At this stage, reliable physical-archaeological models (PAM) will be developed. The final stage of the research will consist of direct archaeological excavations guided by the established PAM.

1. INTRODUCTION

In 1966, Gobustan was declared a state reserve in Azerbaijan, and in 2007, it was inscribed on the UNESCO World Heritage List. The Gobustan area is well known worldwide for its extensive distribution of mud volcanoes (e.g., Aliyev et al., 2015) and rock paintings (e.g., Rustamov, 2003; Farajova, 2018). Meanwhile, given the centuries-long history of human presence in this area, it is likely to contain a wealth of historical information, including a greater number of yet undiscovered cultural objects, beyond the two phenomena mentioned above. The Israeli and international experiences suggest that a variety of geophysical methods can be effectively applied to locate different types of buried archaeological objects. These methods include magnetic prospecting (Eppelbaum, 2011, 2015), the very low frequency method (Eppelbaum, 2021), the self-potential method (Eppelbaum, 2020), near-surface temperature surveys (Eppelbaum, 2009), and microgravity (Eppelbaum, 2025). Given the complex and variable geological conditions in the area, these geophysical methods will be applied to the zones identified through satellite imagery analyses.

Our preliminary remote sensing (RS) analysis of satellite imagery in the region indicates the presence of various archaeological objects, presumably dating to different epochs, that have neither been documented nor mentioned in existing literature. This suggests that non-invasive remote sensing methods can serve as an initial step in the investigation, after which the most promising targets can be examined using LiDAR and surface geophysical methods. Such an approach is particularly relevant because the archaeological objects in this area may contain subsurface layers extending several meters deep.

Based on numerous innovative technologies, remote sensing is a powerful tool for detecting a variety of previously unknown targets (e.g., Eppelbaum et al., 2024; Khabarova et al., 2024; Birkenfeld et al., 2026). The most illustrative archaeological objects identified through remote sensing are qanats, underground aqueducts constructed using ancient techniques developed over thousands of years. The key idea is to connect the uphill water source to settlements and fields downhill, where there are no rivers, lakes, or groundwater lenses, so gravity works in humans' favor. The underground channels enabled avoiding water contamination, evaporation, and heating. The extension of qanats may reach tens of kilometers.

Qanats were first invented in the ancient Persian Empire and were later adopted by Greek, Roman, and Muslim civilisations. From an aerial perspective, the qanats mainly built during the Achaemenid Empire period can be recognised by a series of evenly spaced vertical shafts used during the construction of the underground water channels (Buławka et al., 2024). In modern Iran, many qanats that are thousands of years old remain functional, although the shaft openings are sometimes only detectable from above through variations in soil color or vegetation patterns. Therefore, identified qanats could be used to access underground water resources. The concept is frequently discussed in the literature (e.g., Endreny and Gokcekus, 2009; Nasiri and Mafakheri, 2015; Abedi et al., 2023; Mohajerani et al., 2024). Although thousands of qanats are known in Azerbaijan, for the first time our study reports the presence of numerous qanat shafts in the Gobustan area.

2. METHOD AND DATA

This study forms part of a larger research initiative exploring the use of remote sensing in archaeological investigations. Within this framework, the focus lies on the archaeological landscape of Gobustan, employing an integrated methodology that combines high-resolution satellite imagery, geophysical modeling, and comparative spatial analysis (Eppelbaum et al., 2024; Khabarova et al., 2024). The study relied on imagery from multiple satellite platforms, including Google Earth Pro (Maxar Technologies), CNES/Airbus, and the Pleiades constellation, with spatial resolutions ranging from 2 meters in multispectral bands to 0.5 meters in the panchromatic band. A key aspect of the approach was temporal layering: images captured in different seasons and across multiple years were overlaid to highlight subtle landscape features shaped by variations in shadow, vegetation, and seasonal soil moisture. This combination of spatial and temporal data enabled the detection of features that might otherwise remain invisible, forming the foundation for subsequent geophysical surveys and comparative spatial analysis.

Unlike many other archaeological features, whose origins and functions often remain uncertain when analysed using remote sensing techniques, qanats exhibit relatively straightforward morphological characteristics, forming linear alignments of vertical shafts that are discernible in aerial or satellite imagery. At ground level, these structures are often unrecognisable, as individual shafts are spaced several meters apart and may be detectable only through subtle variations in soil color or vegetation patterns. Systematic analysis of high-resolution satellite and aerial imagery enables the identification and mapping of these features, providing a reliable non-invasive method for documenting their spatial distribution.

3. INFORMATIONAL APPROACH

It is well known that most inverse problem solutions in geophysics are ill-posed. It means, according to Hadamard (1902), that the solution does not exist, is not unique, or is not a continuous function of the observed geophysical data (so that a small perturbation in the observations can cause an arbitrary error in the solution). This fact calls for the broad application of informational and probabilistic methodologies in applied geophysics.

Estimating the information value of geophysical and other means can be formalised based on the following criteria (revised after Eppelbaum et al., 2003) (Figure 1): (1) Informativeness of the application (informational criterion Γ); (2) Cost of implementing the method (cost criterion *C*); (3) Time required to carry out the method (time criterion *T*).

Criteria *C* and *T* are easy to calculate directly, but criterion Γ is a non-trivial research problem. A simplified algorithm can be written as:

$$\Omega = \Gamma \cup C \cup T, \qquad (1)$$

where $\cup$ is the symbol of the unification.

All the available archaeological/geological information can be represented as the classic three-level model (Figure 1): (a) syntactic – quantity of information, (b) semantic – content of information, and (c) pragmatic – value of information. The logical-heuristic model for describing environmental information thus takes the following form (Eppelbaum et al., 2003):

$$\Gamma = I \cup R \cup V, \qquad (2)$$

where *I* is the quantitative estimation of information, *R* is the estimation of informational reliability corresponding to the semantic criterion, and *V* is the estimation of informational value in terms of feasibility according to the pragmatic criterion.

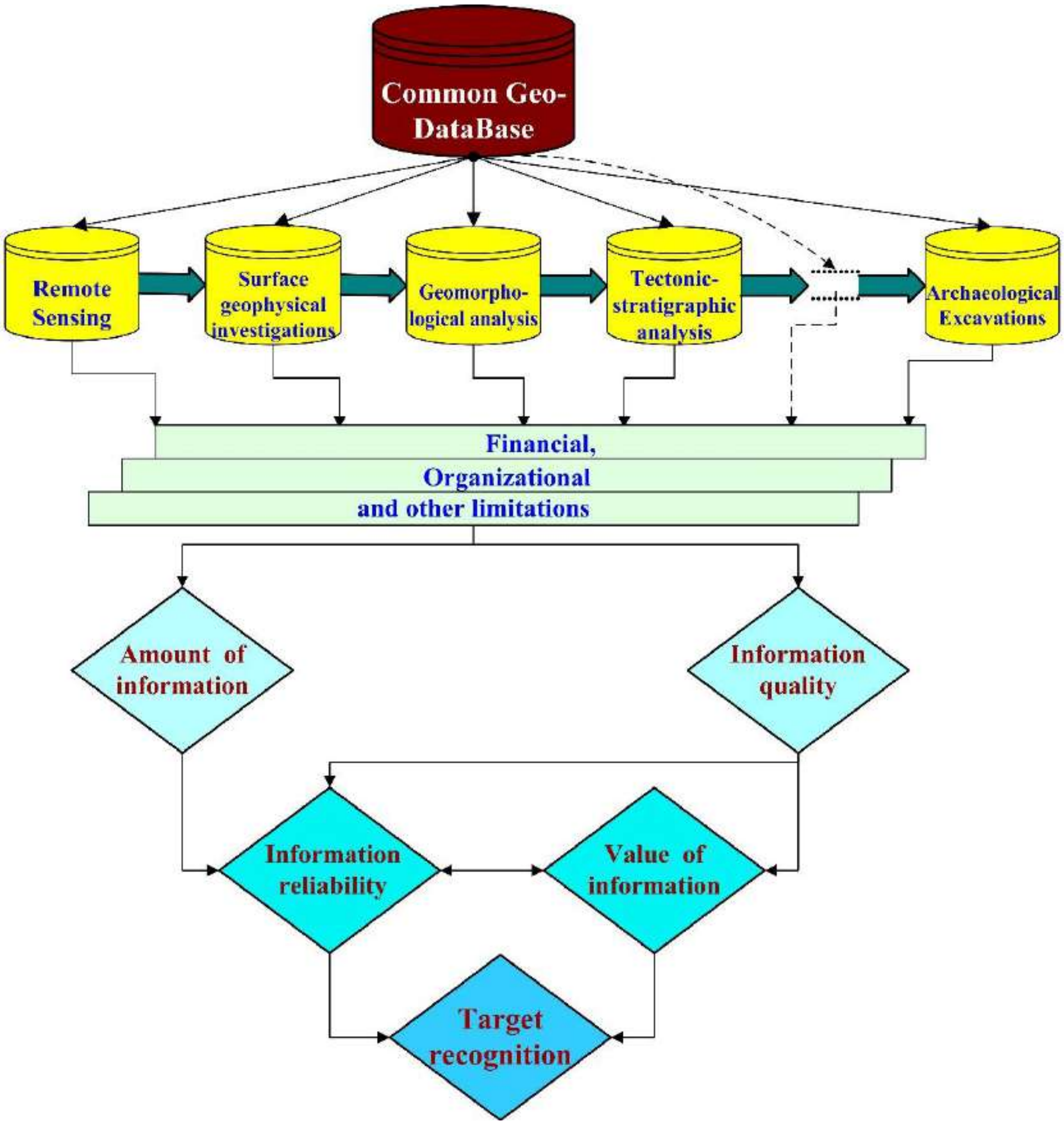

Fig. 1. General scheme for accumulating and processing geospatial information

Algorithm (2) is based on the fundamental terms of information theory and is combined with the structural (hierarchical) approach. This approach defines each indicator as a structure that reflects a set of typical situations and then uses the information measure to calculate the value of each estimator. Parameters V and R should be estimated archaeologically, but this is beyond the scope of this paper. Here, parameters V and R will be neglected, and it is assumed that $\Gamma = I$.

4. EXAMPLES OF REMOTE SENSING DATA ANALYSIS IN GOBUSTAN

RS multidisciplinary analysis has been recognised as a powerful tool for discovering subsurface archaeological targets (Kadhim and Abed, 2023; Tiwari et al., 2023; Eppelbaum et al., 2024; Khabarova et al., 2024). Machine learning techniques can be used to make integrated studies more effective. Applied to archaeology, machine learning (or computer vision methods) has significantly transformed RS data analysis by enabling advanced algorithms to process vast quantities of imagery from satellites and aerial platforms (Davis, 2019). Examples are given in Figures 2 and 3.

The complex physical-geological conditions of the Gobustan region complicate the application of surface geophysical methods. In contrast, satellite imagery provides extensive spatial coverage, including high-resolution images of most terrestrial landscapes. Freely accessible imagery often achieves a spatial resolution of approximately 0.5 meters, sufficient to detect archaeological features at the surface, even when the objects are located several meters below it. This resolution enables the identification of a wide range of environmental and industrial archaeological structures. Among the most significant features found in this study are qanats, as illustrated in Figures 2 and 3. Both figures show qanats approximately 10 km in length, which we identified through the analysis of multi-year satellite imagery. The yellow dashed lines indicating their locations are intentionally offset to avoid overlapping with the underlying patterns. Although linear sequences of shafts may be obscured in areas affected by sediment deposition or anthropogenic disturbances, numerous qanats connecting former river courses with settlements or agricultural fields at lower elevations were identified, with three traceable over several kilometers.

Fig. 2. Preliminary results of the qanat (kehriz) discovery in the Gobustan area (I). The yellow-dashed line follows the qanat shaft line, which may be traced up to several kilometers from the inlet. Satellite images are taken in May 2009 (main image) and October 2023 (enlarged area). The distance between shafts is 4-5 m

Determining the chronological age of these structures is currently not possible, and on-site investigations are required for accurate dating. However, dating qanats is inherently challenging, as accessing the underground channels is both technically difficult and potentially hazardous. Furthermore, qanats may contain limited stratigraphic information or incorporate artifacts from multiple periods, as flowing water can erode surrounding deposits and transport older materials into the channel, complicating the interpretation of their temporal context. As the next step, the RS analysis must be combined with geophysical and geochemical methods.

Fig. 3. Preliminary results of the qanats (kehriz) discovery in the Gobustan area (II). The yellow-dashed lines crossing the river highlight the qanat location. The yellow arrow indicates the irrigation canal

5. DISCUSSION AND CONCLUSIONS

Qanats, underground water systems, have been in continuous use since their invention in the Persian Empire approximately 3,000 years ago and remain functional in many regions today. These structures are widely distributed across the South Caucasus, Central Asia, and the Near and Middle East. In this study, we report the discovery of qanats in Gobustan, located approximately 70 km southwest of Baku, Azerbaijan, using remote sensing techniques. The presence of qanats in Gobustan has not been documented in previous reviews or reference works (e.g., Guliyev, 2021). Their distinct linear arrangement and repeated patterns clearly exclude natural or geological processes as a plausible explanation for these features.

It should be emphasised that the identified qanats represent only one category of the detected ancient features. Other archaeological objects observed in the area include: (1) the ruins of a columned structure, possibly a temple, tentatively attributed to the ancient Roman period; (2) elongated polished stone slabs on mountaintops, measuring 200–300 meters in length, whose alignment and surface treatment are unlikely to be natural; (3) traces of artificial ponds, some tens of meters in diameter, some of which were probably used for extracting chemicals from the volcano mud. Humans could have utilised mud deposits primarily for clay, plaster, and pigments derived from iron and manganese oxides abundant in the area (e.g., Hajiyeva et al., 2025); (4) wide channels (presumably, irrigation canals) and narrow channels associated with the ponds, running parallel over several kilometers; and (5) remains of multiple settlements located both in the valleys and on the slopes of mud volcanoes.

The solution to this "four colors" mathematical problem (Eppelbaum, 2014) shows that two independent geophysical methods are sufficient to characterise archaeological potential. We propose to apply two independent geophysical methods together: Remote Sensing and high-precision magnetic prospecting (Figure 4).

A unique interpretation system has been developed for analyzing magnetic fields in complex physical-geological environments: oblique magnetisation, rugged terrain relief, and the superposition of magnetic fields of various ranks (Eppelbaum et al., 2001; Eppelbaum, 2011, 2015).

The integrated analysis of RS and magnetic survey datasets can be performed by calculating threshold pixels using color classification or by evaluating the magnitude and directional coherence of vector fields (Eppelbaum et al., 2025). In the most promising areas identified, supplementary investigations using low-altitude LiDAR surveys at 30–40 meters may be required to refine the detection of subtle surface and subsurface features. The combined application of these two independent geophysical methods, high-resolution RS and detailed magnetic surveys, will facilitate the construction of robust physical-archaeological models. These models can subsequently guide targeted, direct archaeological excavations, maximising the efficiency and accuracy of field investigations.

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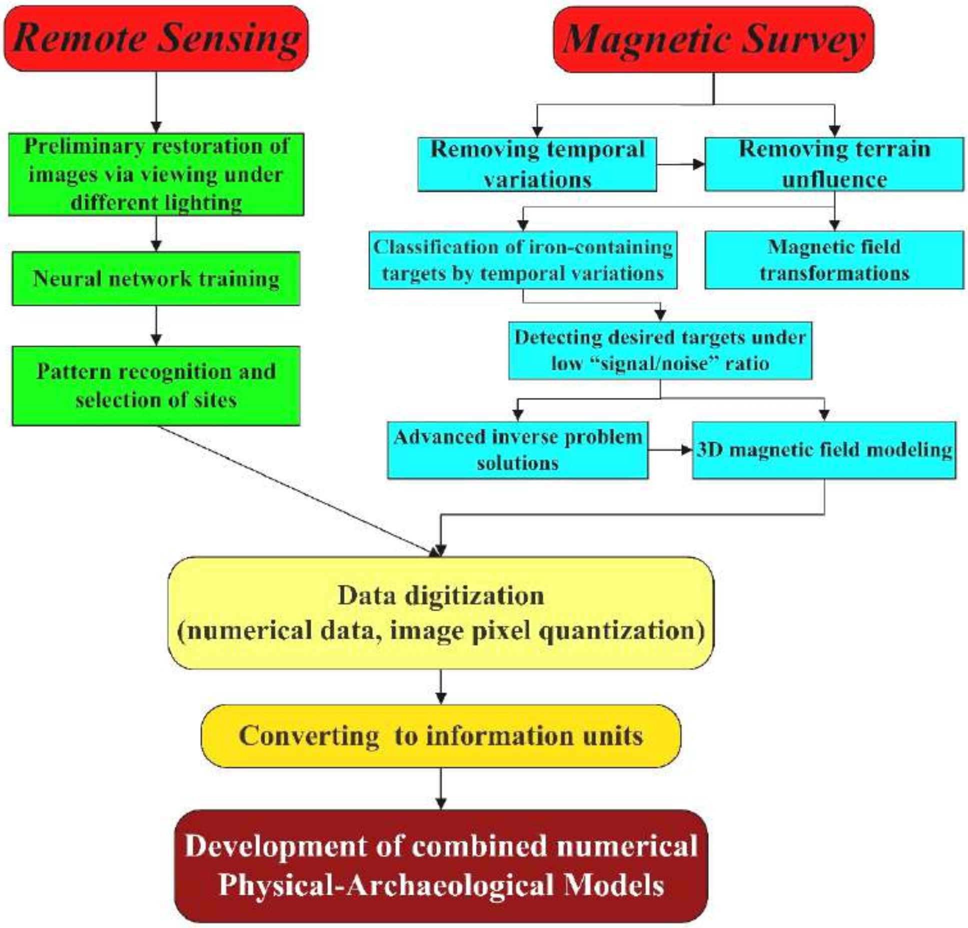

Fig. 4. A generalised flow-chart of combined Remote Sensing and magnetic investigations

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ОБНАРУЖЕНИЕ КЯРИЗОВ В ГОБУСТАНЕ ПО ДАННЫМ ДИСТАНЦИОННОГО ЗОНДИРОВАНИЯ ВЫСОКОГО РАЗРЕШЕНИЯ

Хабарова О.В.[1]* and Эппельбаум Л.В.[2,3]

[1]*Междисциплинарный центр безопасности, надежности и уверенности, Люксембургский университет, Люксембург L-1855, Люксембург, просп. Кеннеди, 29*

[2]*Кафедра геофизики, Факультет точных наук, Тель-Авивский университет, Израиль Рамат Авив 6997801, Тель-Авив*

[3]*Азербайджанский Государственный Университет Нефти и Промышленности, Азербайджан AZ1010, Баку, просп. Азадлыг, 20*

**Автор, отвечающий за переписку: olga.khabarova@uni.lu*

Резюме. Недавние исследования демонстрируют эффективность интегрированных археогеофизических инструментов в решении широкого спектра геологических и экологических задач. Этот подход сочетает геофизические методы с археологическими полевыми работами или дистанционным зондированием для поддержки предварительного обследования и анализа археологических объектов, потенциально дополненного методами машинного обучения для оценки форм и характеристик подземных объектов. Настоящее исследование подчеркивает ценность информационных и вероятностных подходов как оптимальных инструментов для оценки и интеграции критически важных данных для археологических исследований. Мы использовали дистанционное зондирование для обнаружения археологических объектов в Гобустанском регионе Азербайджана, который был внесен в Список всемирного наследия ЮНЕСКО в 2007 году, и продемонстрировали существенный потенциал комбинированного археогеофизического анализа для выявления различных древних исторических объектов в этом районе. Для анализа свободно доступных данных дистанционного зондирования за разные годы и миссии были применены передовые методы интерпретации. Мы выявили сложную ирригационную систему, характерную для периода империи Ахеменидов, простирающуюся за пределы Гобустанского национального заповедника и включающую взаимосвязанные каналы, искусственные озера и пруды, ассоциирующиеся с близлежащими поселениями. Древние кяризы, легко идентифицируемые на спутниковых снимках, относятся к числу наиболее убедительных находок, ранее не документированных в этой области. Следующий этап исследования будет включать применение анализа магнитного поля на поверхности (или на малой высоте), в том числе качественную и количественную интерпретацию аномалий и трехмерное моделирование. На этом этапе будут разработаны надежные физико-археологические модели (ФАМ). Заключительный этап исследования будет состоять из непосредственных археологических раскопок, проводимых в соответствии с разработанными ФАМ.

Ключевые слова: *Дистанционное зондирование, Гобустан, кяризы, комбинированный геофизический анализ, информационный подход*

QOBUSTANDA KƏHRİZLƏRİN YÜKSƏK DƏQİQLİKLİ UZAQDAN ZONDLAMA MƏLUMATLARI ƏSASINDA MÜƏYYƏNLƏŞDİRİLMƏSİ

Xabarova O.V.[1]* və Eppelbaum L.V.[2,3]

[1]*Təhlükəsizlik, Etibarlılıq və Etibar üzrə Fənlərarası Mərkəz, Lüksemburq Universiteti, Lüksemburq*

[2]*Geofizika kafedrası, Dəqiq Elmlər Fakültəsi, Tel-Əviv Universiteti, İsrail Ramat-Əviv 6997801, Tel-Əviv*

[3]*Azərbaycan Dövlət Neft və Sənaye Universiteti, Azərbaycan Azadlıq prospekti, 20, Bakı, AZ1010*

**Yazışmalara cavabdeh olan müəllif: olga.khabarova@uni.lu*

Xülasə. Son tədqiqatlar göstərir ki, inteqrasiya olunmuş arxeo-geofiziki alətlər geniş spektrli geoloji və ekoloji problemlərin həllində yüksək effektivliyə malikdir. Bu yanaşma arxeoloji sahə işləri və ya uzaqdan zondlama ilə geofiziki metodların birləşdirilməsinə əsaslanır və arxeoloji obyektlərin ilkin tədqiqi və təhlilini dəstəkləyir; həmçinin yeraltı obyektlərin forma və xüsusiyyətlərini qiymətləndirmək üçün maşın öyrənməsi texnikaları ilə gücləndirilə bilər. Təqdim olunan tədqiqat arxeoloji araşdırmalar üçün mühüm məlumatların qiymətləndirilməsi və inteqrasiyası baxımından informasiya və ehtimal yanaşmalarının optimal alətlər kimi əhəmiyyətini vurğulayır. Biz Qobustan regionunda arxeoloji obyektlərin müəyyənləşdirilməsi üçün uzaqdan zondlama metodlarından istifadə edirik; bu ərazi 2007-ci ildə UNESCO World Heritage List-nə daxil edilmişdir. Tədqiqat bu ərazidə müxtəlif kateqoriyalara aid tarixi strukturların aşkar edilməsində kombinə olunmuş arxeo-geofiziki analizlərin böyük potensialını nümayiş etdirir. Müxtəlif illərə və missiyalara aid sərbəst əldə edilə bilən uzaqdan zondlama məlumatlarının təhlili üçün qabaqcıl interpretasiya metodologiyaları tətbiq edilmişdir. Biz Əhəmənilər dövrünə xas olan, Qobustan Milli Qoruğunun hüdudlarından kənara çıxan və bir-biri ilə əlaqəli kanalları, süni gölləri və gölməçələri əhatə edən, yaxınlıqdakı yaşayış məntəqələri ilə birləşdirilən mürəkkəb suvarma sistemini müəyyən etdik. Peyk görüntülərində asanlıqla müəyyən edilə bilən qədim kəhrizlər bu ərazidə əvvəllər sənədləşdirilməmiş ən cəlbedici tapıntılar sırasındadır. Tədqiqatın növbəti mərhələsində səthi (və ya aşağı hündürlüklü) maqnit sahəsi analizləri, o cümlədən anomaliyaların keyfiyyət və kəmiyyət baxımından şərhi və üçölçülü modelləşdirmə həyata keçiriləcəkdir. Bu mərhələdə etibarlı fiziki-arxeoloji modellər (PAM) hazırlanacaqdır. Araşdırmanın yekun mərhələsi isə formalaşdırılmış PAM əsasında istiqamətləndirilən birbaşa arxeoloji qazıntılardan ibarət olacaqdır.

Açar sözlər: *Məsafədən zondlama, Qobustan, kəhriz, kombinə edilmiş geofiziki analiz, informasiya yanaşması*