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Su Kaynakları ve Sürdürülebilir Su Yönetimi
Water Resources and Sustainable Water Management

TMMOB JEOLOJİ MÜHENDİSLERİ ODASI
Chamber of Geological Engineers of Türkiye

Makale Gönderim Adresi:
TMMOB Jeoloji Mühendisleri Odası
PK. 464 Yenişehir, 06410 Ankara
Tel : (0312) 434 36 01
Faks : (0312) 434 23 88
E-Posta : jmo@jmo.org.tr
https://dergipark.org.tr/tr/pub/jmd

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Kazım Karabekir Cad. Altuntop İşhanı
No:87/7 İskitler/Ankara
Tel : (0312) 384 54 88
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İçindekiler / *Contents*

Makaleler / Articles

ÖNSÖZ

Su kaynaklarının sürdürülebilir yönetimi, günümüzde hem bilimsel hem de toplumsal açıdan en kritik konular arasında yer almaktadır. İklim değişikliğinin hızlanan etkileri, şehirleşme baskısı, kuraklık, su güvensizliği, sedimantasyon sorunları ve artan su talebi, su kaynaklarının korunması ve geleceğe güvenle aktarılmasını zorunlu kılmaktadır. Bu kapsamda hazırlanan Jeoloji Mühendisliği Dergisi "Su Kaynakları ve Sürdürülebilir Su Yönetimi" Özel Sayısı, alana yönelik güncel yaklaşımları, yöntemleri ve araştırma sonuçlarını içeren altı özgün bilimsel çalışmayı bir araya getirmektedir.

Bu özel sayıda yer alan çalışmalar; uydu yağış verilerinin yer gözlemleriyle doğrulanması, küresel literatürde su güvenliği eğilimlerinin bibliyometrik analizi, jeotermal sistemlerde CO_2 tutulumu sırasında mineral tepkimeleri, yapay zekâ kullanılarak su tüketiminin tahmini, Akdeniz havzalarında sediman taşınım modelleri ve büyük kent havzalarının geleceğe dönük su yönetim senaryoları gibi çok çeşitli temaları kapsamaktadır. Bu yönüyle sayı, hem yerel hem de küresel ölçekte su kaynaklarına ilişkin güncel bilimsel tartışmalara katkı sunmakta; araştırmacılar, mühendisler, karar vericiler ve uygulayıcılar için yeni bir perspektif oluşturmaktadır.

Bu Özel Sayının hazırlanmasına değerli katkıları nedeniyle, Misafir Editörler Prof. Dr. Hüseyin Gökçekuş ve Doç. Dr. Youssef Kassem'e en içten teşekkürlerimizi sunarız. Ayrıca titiz değerlendirmeleriyle bilimsel niteliğin gelişmesine katkı sağlayan hakemlere ve çalışmalarını sayıya kazandıran tüm yazarlara teşekkür ederiz.

Bu sayının, disiplinler arası sürdürülebilir su kaynakları hakkında etkileşimi güçlendirmesini, sürdürülebilir su yönetimi konusundaki araştırmalara ivme kazandırmasını ve geleceğe yönelik yeni bilimsel çalışmalara ilham vermesini diliyoruz.

Jeoloji Mühendisliği Dergisi
Editör Kurulu adına
Prof. Dr. Tolga ÇAN

PREFACE

Sustainable water management has become one of the most pressing global challenges as climate change, rapid urbanization, increasing water demand, sedimentation problems, and water insecurity continue to intensify. In this context, the Special Issue of the Journal of Geological Engineering on "Water Resources and Sustainable Water Management" brings together six original scientific contributions, each addressing different dimensions of water-related issues through contemporary approaches and methodologies.

The articles in this volume examine a wide range of topics, including the validation of satellite-based precipitation products, bibliometric trends in global water security research, mineral reaction kinetics during CO_2 sequestration in geothermal systems, artificial intelligence applications for water consumption forecasting, sediment dynamics within Mediterranean basins, and future-oriented water management strategies for metropolitan sub-basins. Collectively, these studies provide valuable insights for researchers, engineers, policymakers, and practitioners working on the sustainable use and governance of water resources.

We extend our sincere appreciation to the Guest Editors, Prof. Dr. Hüseyin Gökçekuş and Assoc. Prof. Dr. Youssef Kassem, for their dedicated efforts in shaping and coordinating this Special Issue. We also thank all reviewers for their rigorous evaluations and the authors for their meaningful scientific contributions.

We hope that this issue will strengthen interdisciplinary interaction on sustainable water resources, accelerate research on sustainable water management, and inspire new scientific studies in the years to come.

On behalf of the Editorial Board of the
Journal of Geological Engineering
Prof.Dr. Tolga ÇAN

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Araştırma Makalesi / *Research Article*

Evaluation of GPM-IMERG V07 Precipitation Data Against In-Situ Measurements in a Semi-Arid Region of Türkiye

Türkiye'nin Yarı Kurak Bölgesi için Tahmin Edilen GPM-IMERG V07 Yağış Verilerinin Gerçek Gözlemlerle Karşılaştırılması

Omar ALSENJAR , Mahmut ÇETİN
Department of Agricultural Structures and Irrigation, Cukurova University, Adana, Türkiye

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ABSTRACT

Accurate precipitation data are essential for hydrological modeling, water resource management, and climate impact assessments, particularly in semi-arid regions that are increasingly affected by water scarcity. Satellite-based products, such as the *Global Precipitation Measurement (GPM)* mission's *Integrated Multi-satellite Retrievals for GPM (IMERG) Final Run Version 07 (V07)*, may offer a valuable alternative to sparse and unevenly distributed ground-based observations. The primary objective of this study is to assess the performance of GPM IMERG V07 precipitation estimates for the semi-arid region of southern Türkiye by comparing them with gauge data from Adana Meteorological Station for the period 1998–2024. Statistical evaluation was conducted using the coefficient of determination (R^2), Pearson's correlation coefficient (r), and root mean square error (RMSE) at both monthly and yearly scales. Furthermore, F-tests and Student t-tests were applied to assess differences in precipitation variability and mean values between satellite and ground observations. Results indicate that IMERG V07 exhibits strong agreement with in-situ measurements, with high correlation values ($r \approx 0.95$) and RMSE of 23.02 mm/month and 158.63 mm/year, demonstrating its reliability in capturing precipitation dynamics. Nonetheless, despite the strong correlation, IMERG V07 systematically overestimates precipitation totals. This trend of overestimation, confirmed through Student t-tests, suggests that correction methods must be applied to enhance the accuracy of the data before it is used in hydrological and water resource applications. Overall, the findings support the utility of IMERG V07 as a robust precipitation dataset in data-scarce environments like semi-arid regions, provided that its systematic deviation is effectively addressed.

Keywords: Satellite precipitation products, GPM IMERG, semi-arid region, satellite validation, Türkiye

ÖZ

Yağış verileri, özellikle su kıtlığından giderek daha fazla etkilenen yarı kurak bölgelerde hidrolojik modelleme, su kaynakları yönetimi, iklim değişikliği ve etkilerinin değerlendirilmesine yönelik çalışmalarda büyük önem taşımaktadır. Küresel Yağış Ölçüm (GPM) misyonunun Entegre Çoklu Uydu Türevleri (IMERG) Nihai Ürün Sürüm 07 (V07) gibi uydu tabanlı ürünler, seyrek ve düzensiz dağılmış meteoroloji gözlem istasyonları gözlemlerine bir alternatif olmaktadır. Bu çalışmada, 1998–2024 döneminde Türkiye'nin güneyindeki yarı kurak bir bölgede IMERG V07 yağış tahminlerinin, aylık ve yıllık yağış gözlem verileriyle karşılaştırılarak kullanılabilirliğinin ortaya konulması amaçlanmıştır. Amaç doğrultusunda, Adana Meteoroloji İstasyonundan alınan veriler kullanılmıştır.

Sorumlu yazar / *Corresponding author:* omarsenjar@yahoo.com

İstatistiksel kıyaslamalar, aylık ve yıllık ölçeklerde belirleme katsayısı (R^2), Pearson korelasyon katsayısı (r) ve ortalama karekök hata (RMSE) kullanılarak gerçekleştirilmiştir. Ayrıca, uydu ve yer gözlemleri arasındaki yağış değişkenliği ve ortalama değerlerin istatistiksel anlamda farklı olup olmadığının ortaya konulmasında, F-testi ve Student t-testi kullanılmıştır. Sonuçlar, IMERG V07'nin yer gözlemleriyle yüksek düzeyde uyum sağladığını, korelasyon değerlerinin yüksek olduğunu ($r \approx 0.95$) ve RMSE değerlerinin aylık 23.02 mm ve yıllık 158.63 mm olduğunu göstermiştir. Bu durum, yağış dinamiklerini yakalama konusunda IMERG V07'nin güvenilirliğini ortaya koymuştur. Veri setleri arasındaki güçlü korelasyona rağmen, IMERG V07'nin yağış toplamlarını sistematik olarak fazla tahmin ettiği saptanmıştır. Student t-testleri ile doğrulanan bu aşırı tahmin eğilimi, GPM-IMERG V07 veri setlerinin hidrolojik modelleme, su kaynaklarının planlanması vb. uygulamalarda kullanılmadan önce, temsil niteliğini (doğruluğunu) artırmak amacıyla düzeltme yöntemlerinin uygulanmasının gerekliliğine işaret etmektedir. Araştırma bulguları bir bütün olarak değerlendirildiğinde, IMERG V07'nin yarı-kurak ve veri yetersizliği olan bölgelerde güçlü bir yağış verisi seti olarak kullanılabileceği; ancak, verilerdeki yanlılığın (sistematik sapmanın) uygun bir yöntem kullanılarak giderilmesi gerektiği sonucuna varılmıştır.

Anahtar Kelimeler: *Uydu yağış ürünleri, GPM IMERG, yarı kurak bölge, uydu doğrulama, Türkiye*

INTRODUCTION

Precipitation (P) is a fundamental component of the Earth's hydrological cycle, directly affecting planning of irrigation and drainage schemes, water resources management, and the occurrence of floods and droughts. Accurate and timely precipitation measurements are essential for addressing a range of scientific and practical challenges, including drought monitoring, flood forecasting, irrigation planning, and assessments of climate change (Aksu and Akgul, 2020). Precipitation is a fundamental component of the hydrological cycle, contributing to the sustainability of water resources and supporting both environmental systems and anthropogenic demands. For example, it plays a crucial role in replenishing groundwater, in human consumption, and in limiting the decline in freshwater abstraction from aquifers in the Eastern Mediterranean region of Türkiye, especially in the Cukurova region. Significant temporal and regional variability may be seen in P patterns, which are impacted by geographic factors, land cover dynamics, and climate change. To improve hydrological evaluations and support decision-making for sustainable resource management, high-quality data at various spatial and temporal scales is essential for a better understanding of these patterns.

Traditionally, precipitation data have been obtained using ground-based methods, including various types of rain gauges—such as the National Oceanic and Atmospheric Administration (NOAA) standard, simple, tipping-bucket, optical, and piezoelectric—and meteorological monitoring stations. Although these instruments provide high accuracy at specific locations, their limited number and spatial coverage, particularly in mountainous and rural areas, pose significant challenges for comprehensive hydrological monitoring (Reddy and Saravanan, 2023). Therefore, satellite-based precipitation estimation has emerged as a complementary approach, offering broad spatial coverage and frequent updates. Among these, the Global Precipitation Measurement (GPM) mission, launched in 2014 as a joint initiative by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), represents a milestone in global precipitation observation. GPM aims to provide advanced, high-resolution precipitation data globally, using a constellation of satellites equipped with passive microwave and radar sensors (Huffman et al., 2019a, 2019b).

The core instruments of the GPM mission include the Dual-frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI), enhancing precipitation detection, particularly for light rainfall and snowfall. The mission's primary product, the Integrated Multi-satellite Retrievals for GPM (IMERG), combines data from multiple sensors to produce precipitation estimates at high spatial resolution of 0.1° (~10 km) and a temporal resolution of 30 minutes. IMERG has been widely adopted in hydrological, meteorological, and climate-related research due to improved accuracy compared to its predecessor, the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2019a; Islam et al., 2020; Moazami and Najafi, 2021; Aksu and Yaldiz, 2025). NASA's latest IMERG release (Version 07) introduces significant updates, and users have been advised not to mix it with earlier versions due to methodological differences (Aksu and Yaldiz, 2025). Given its high resolution and capacity to capture extreme precipitation events, IMERG V07 may be a suitable dataset for regional-scale hydro-meteorological studies. Nevertheless, the validation of these datasets with ground-based measurements is consistently necessary to ensure their reliability.

Several regional studies assessed the accuracy of GPM-IMERG products against in-situ precipitation observations. Moazami and Najafi (2021) assessed the accuracy of IMERG V06 against Canadian ground gauges at both hourly and daily scales (2014–2018), concluding that both IMERG V06 and Multi-Radar Multi-Sensor (MRMS) Precipitation Rate data can effectively complement ground observations. Islam et al. (2020) found that IMERG and the Multi-satellite Precipitation Analysis (TMPA) outperformed other satellite products. Their study compared these datasets with the Climate Prediction Centre Morphing Technique (CMORPH), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), and the PERSIANN-Climate Data Record (PERSIANN-CDR) against ground gauge measurements across Australia over a five-year period from October 2014 to September 2019. Similarly, various studies have been conducted to evaluate their effectiveness in diverse geographical and climatic settings (Le et al., 2020; Reddy and Saravanan, 2023; Watters et al., 2024). In semi-arid regions, including parts of Türkiye, few validation studies have been conducted to assess the accuracy of GPM IMERG products against ground-based observations. For example, Aksu et al. (2023) evaluated the IMERG V06 Final Run using data from 99 meteorological stations across Türkiye between 2010 and 2020. Their results found Pearson's correlation coefficient of 0.64 between IMERG estimates and daily precipitation records. More recently, Aksu and Yaldiz (2025) validated IMERG V07 using observations from 214 ground stations and compared its performance with the previous V06 version from 2010 to 2022. Their findings demonstrated significant improvements in V07 across all seasons, particularly during winter. In this season, the correlation coefficient increased from 0.57 to 0.64, the mean absolute bias declined from 78.22% to 69.27%, and root mean square error (RMSE) was reduced from 11.10 mm/day to 9.70 mm/day.

The monthly precipitation estimates from IMERG V07 have potential as reliable inputs for calculating water balance, meteorological drought indices such as Standardized Precipitation Index (SPI) and Standardized

Precipitation Evapotranspiration Index (SPEI) (Yuan and Lia, 2025), and agricultural indicators, particularly in semi-arid areas where ground gauge data are scarce. Moreover, GMP IMERG V07 can be used to capture extreme precipitation indices. While GPM-IMERG V07 is extensively utilized for precipitation monitoring, validation with long-term precipitation data from the Adana meteorological station and its surrounding region is limited. Given the critical role of accurate precipitation data in agriculture and water management, this study evaluates the GPM IMERG V07 product by validating it against ground-based observations from the Adana Meteorological Station from 1998 to 2024 at monthly and yearly scales. The evaluation employs statistical metrics, including the correlation coefficient (r) and RMSE. Furthermore, F-tests and t-tests were conducted to compare the variability and mean rainfall values between satellite estimates and ground-based measurements, in order to assess the suitability of GPM IMERG data for hydrological modeling and climate impact assessments. We believe that the findings will provide valuable insights for stakeholders, researchers, and policymakers regarding the strengths and limitations of satellite precipitation data, supporting improved modeling, forecasting, and resource planning under evolving climate conditions.

MATERIALS AND METHODS

Study Area

This study focuses on Adana Province (14,030 km^2) in Türkiye's Eastern Mediterranean, a fertile and densely populated region with a typical Mediterranean climate. It lies at the center of the Cukurova (Cilician) Plain, between 36.5°–38.4°N and 35.0°–35.4°E, as shown in Figure 1. The region experiences hot, dry summers and mild, wet winters. According to long-term climate data (1960–2024) from Adana Meteorological Station (*Station No. 17351*, latitude 37.0041° and longitude 35.3441°), the region receives average annual precipitation of 662.4 mm, with nearly 50% falling during the winter months of December through February (Cetin, 2020). The average monthly temperature is about 19.2 °C, with peak temperatures in July and August averaging 28.4 °C and 28.7 °C, respectively. Relative humidity generally exceeds 80% in the summer months, whereas it can fall below 50% during the wet season (Cetin, 2020; Alsenjar et al., 2023a; 2023b).

Adana province, part of the Cukurova region, is vital to Türkiye's agriculture, which is supported by extensive irrigation and diverse crop cultivation. Winter crops include wheat, onions, potatoes, and lettuce, while summer crops predominantly comprise cotton, soybeans, corn, peanuts, and watermelon. In addition, citrus orchards cover a substantial part of the plain, making it one of the country's most fertile and productive agricultural regions (Ozcan et al., 2003; Cetin et al., 2023a; 2023b).

In-situ precipitation data

Observed precipitation data were obtained from the Turkish State Meteorological Service (TSMS, 2023) for Adana Meteorological Station (Station ID: 17351), located approximately 23 meters above sea level. This station has been in operation for decades, with recorded data going back as far as 1928, and is known for high-quality, continuous meteorological records. Daily precipitation data corresponding to the period 1998–2024, matching the timeframe of the IMERG data, were used in the analysis.

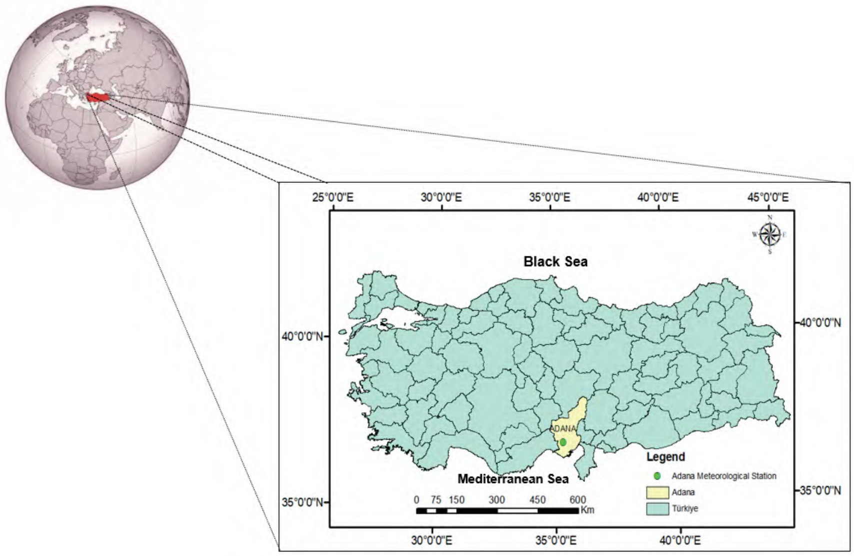


Figure 1. Location of Adana meteorological station (17351) in Türkiye.
Şekil 1. Adana meteoroloji istasyonunun (17351) Türkiye'deki konumu.

This period corresponds to the availability of complete records from IMERG Version 07. As a result, all precipitation data were full with no missing values, eliminating the need for data imputation. The gauge dataset was also visually examined through graphs to ensure consistency. The TSMS used a tipping-bucket rain gauge (200 cm², 0.2 mm/tip) to observe precipitation.

Satellite precipitation data

Satellite precipitation data were obtained from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Version 07 dataset. The IMERG V07 product offers high-resolution global precipitation estimates with a spatial resolution of 0.1° (10 km × 10 km) and a temporal resolution of 3 hours, making it suitable for analyzing precipitation variability and patterns in the study area. The Final Run includes gauge-based corrections (https://gpm.nasa.gov/resources/documents/imerg-v07-release-notes), making it ideal for research and hydrological applications. IMERG integrates data from multiple sensors, including microwave instruments, infrared sensors, and passive/active radar (e.g., DPR aboard GPM Core). These sensors collectively enhance the accuracy and spatial coverage of precipitation estimates. Monthly precipitation data spanning January 1998 to December 2024 were retrieved from the Google Earth Engine (GEE) using the "NASA/GPM_L3/IMERG_MONTHLY_V07" collection. Data extraction and processing were seamlessly integrated between GEE and Python within the Google Colab environment. Further information about the GPM mission and IMERG products is available on NASA's official website (https://gpm.nasa.gov/data/imerg, accessed April 22, 2025). Technical specifications and practical applications of these products were further detailed by Aksu and Yaldiz (2025).

Comparison of GPM IMERG V07 with in-situ precipitation measurements

To ensure consistency in the comparison, the IMERG grid cell corresponding to the coordinates of Adana Meteorological Station was extracted using the GEE platform. Monthly and yearly IMERG values were compared using a point-to-pixel approach to avoid uncertainties associated with interpolation methods applied to point-based precipitation data (Xu et al., 2015) from 1998 to 2024.

This study investigated the discrepancies between in-situ precipitation measurements and GPM IMERG V07 estimates across the study area using simple linear regression. In addition, a comprehensive statistical analysis was conducted to evaluate the accuracy and correlation of the dataset, utilizing the coefficient of determination (R^2), Pearson's correlation coefficient (r), and RMSE. Pearson's correlation coefficient is used to evaluate the goodness of fit of the linear relationship, in which a value of 1 is the perfect score (Kronthaler, 2023), as illustrated in Table 1. RMSE represents the average size of the errors between the datasets. Additionally, we conducted statistical tests on monthly and yearly rainfall datasets to evaluate the agreement between the GPM IMERG V07 satellite precipitation product and in-situ rainfall observations. First, an F-test was applied to compare the variances of the two datasets and assess whether the variability in the data differed significantly. Subsequently, parallel to the result of the F-test, a two-sample t-test (Çetin, 1997) was performed to determine if the mean rainfall amounts from the satellite data significantly differed from the ground measurements. These analyses enabled a robust comparison of the rainfall variability and magnitude in the datasets, providing insight into the accuracy and reliability of the GPM IMERG product for hydrological applications.

Table 1. Reference scale for assessing correlation coefficient strength (Kronthaler, 2023).

Çizelge 1. Korelasyon katsayısı gücünün değerlendirilmesine yönelik referans ölçek (Kronthaler, 2023).

Value of r	Correlation between two variables
r= 1	Perfect positive correlation
1 >r≥ 0.6	Strong positive correlation
0.6 >r≥ 0.3	Weak positive correlation
0.3 >r> -0.3	No correlation
-0.3 ≥ r>-0.6	Weak negative correlation
-0.6 ≥r≥ -1	Strong negative correlation
r= -1	Perfect negative correlation

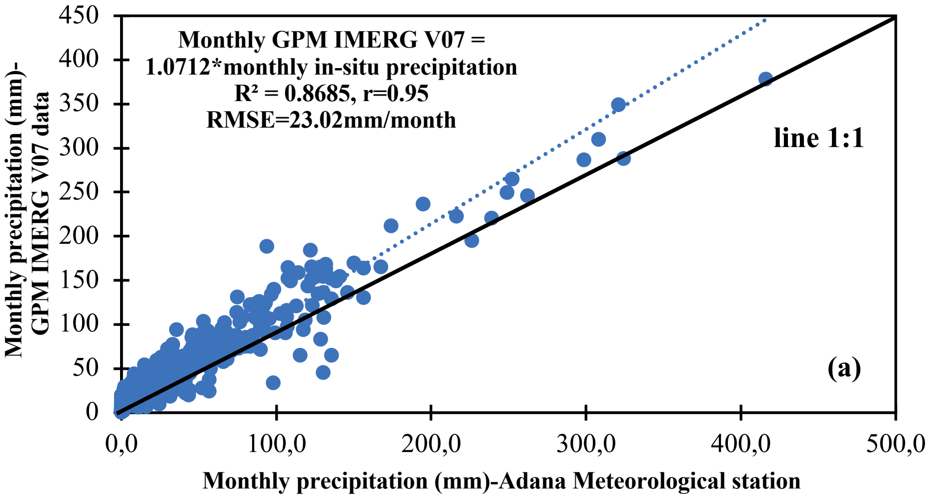
RESULTS AND DISCUSSION

Validation of GPM IMERG V07 precipitation data

To assess the accuracy and applicability of the GPM-IMERG V07B Final Run precipitation estimates, a comprehensive performance evaluation was conducted using ground-based observations from Adana Meteorological Station, covering the period from January 1998 to December 2024. This long-term comparison aimed to validate the reliability of IMERG data for regional hydrological and climate studies. Statistical metrics, including the R^2, r, and RMSE, were employed to evaluate the consistency between satellite-derived and in-situ precipitation measurements at monthly and annual time scales.

Linear regression analysis was performed to quantify the strength of the relationship between the two datasets, with scatter plots generated to represent their alignment visually (Figure 2). The results demonstrated a consistently strong correlation across temporal scales. At the monthly level, IMERG V07 exhibited a high correlation with observed precipitation (r = 0.95), accompanied by relatively low RMSE of 23.02 mm/month. On a yearly basis, the agreement remained robust, with an identical correlation coefficient (r = 0.95) and RMSE of 158.63 mm/year. This annual RMSE represents approximately 25% of the mean annual precipitation (629 mm from 1998 to 2024), which is considered moderate and acceptable for satellite-based products. Additionally, monthly and yearly temporal variations shown on time series plots indicated that the GPM-IMERG product successfully captured the temporal pattern of precipitation events, as shown in Figure 3. Figure 3 illustrates that GPM IMERG V07 precipitation estimates are generally slightly higher (≈7%) than the corresponding in-situ measurements. This discrepancy likely stems from several contributing factors, including the spatial averaging inherent in satellite retrievals compared to the point-based nature of gauge observations, potential overestimation by IMERG algorithms under certain meteorological conditions, and the indirect detection methods influenced by microphysical cloud properties. Notably, the discrepancies were more pronounced in annual precipitation totals than in monthly values.

The statistical analysis comparing GPM IMERG V07 precipitation data with in-situ rainfall measurements revealed no significant difference in the variability of monthly (F-test, $p = 0.1016$) and yearly (F-test, $p = 0.301$) rainfall totals. The variance comparison results indicated that both datasets exhibit similar temporal variability, with no statistically significant difference between their variances. However, the two-sample t-tests showed a statistically significant difference in mean rainfall values at both monthly ($p < 0.0001$) and yearly ($p = 0.0016$) scales, with GPM IMERG consistently overestimating precipitation compared to ground observations. These results suggest that while the satellite product effectively captures rainfall variability and temporal distribution patterns, it consistently overestimates precipitation amounts, indicating a systematic positive bias in rainfall magnitude. This bias may be attributed to algorithmic limitations, sensor calibration issues, or the influence of local climatic and topographic factors (Huffman et al., 2019b; Aksu and Yaldiz, 2025). Although the flat terrain in the study area minimizes elevation-related errors, the overestimation observed in GPM V07 data may also be influenced by microphysical cloud properties—such as droplet size, vertical structure, and phase transitions—that were not fully addressed. These factors, combined with the inherent challenges of detecting light or convective rainfall in semi-arid climates, warrant further investigation to improve satellite precipitation reliability. Such discrepancies often arise from complex meteorological events, such as convective storms or prolonged light rainfall, which are difficult for satellites to capture accurately. Future research leveraging more detailed datasets will enable separate assessments of precipitation type, intensity, and phase, facilitating more precise and comprehensive analyses. Consequently, GPM IMERG V07 can be effectively used for trend and variability analyses. However, it should be bias-corrected or the equations proposed in this study should be used, as mentioned in Figure 2 (*monthly GPM IMERG V07 = 1.0712 × monthly in-situ precipitation; yearly GPM IMERG V07 = 1.2129 × yearly in-situ precipitation*), before direct application in hydrological modeling or water resource management to avoid overestimations. The correction factors were derived solely for Adana station, which may limit their applicability in other regions with different climatic or geographic characteristics. Additionally, these factors may vary over time, especially in long-term climate analyses. This limitation is acknowledged to ensure clarity regarding the broader use of the correction method.



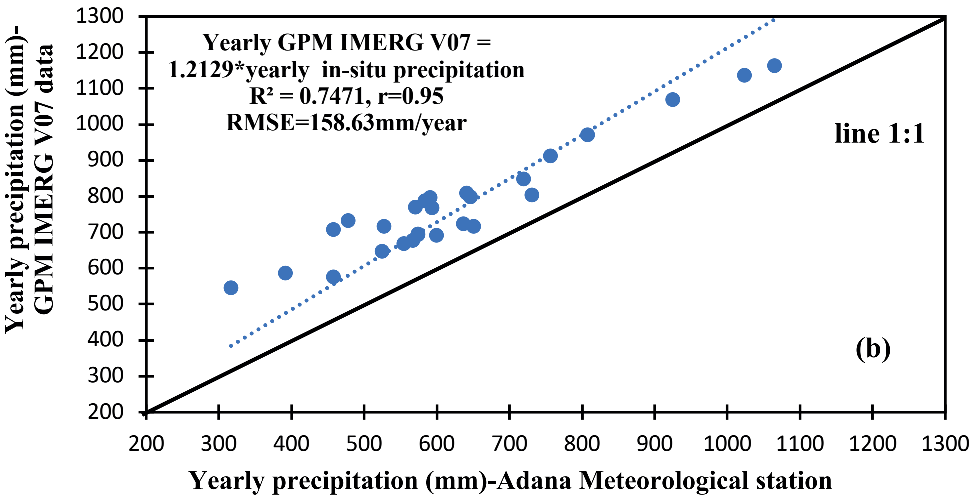


Figure 2. Linear relationship between IMERG V07 and in-situ precipitation observations in Adana at two temporal scales: (a) monthly and (b) annual, for the period 1998–2024.

Şekil 2. 1998–2024 Dönemi için Adana'daki IMERG V07 ve yerinde yağış gözlemleri arasındaki doğrusal ilişki: (a) aylık ve (b) yıllık zaman ölçeklerinde.

As GPM IMERG V07 is a relatively new product, validation efforts remain limited. Wang et al. (2023) demonstrated that V07 outperformed its predecessor (V06) both globally and in China, showing improved accuracy and lower RMSE values. However, issues such as overestimation in coastal areas and underestimation in mountainous regions (e.g., the Tibetan Plateau) were still evident. Similarly, Keikhosravi-Kiany and Balling Jr. (2024) reported modest improvements of V07 for Iran, while systematic underestimation persisted, particularly in high-altitude regions. In Türkiye, Aksu and Yaldiz (2025) conducted a comparative assessment of V07 and V06, concluding that V07 provided more accurate daily precipitation estimates across all regions and seasons.

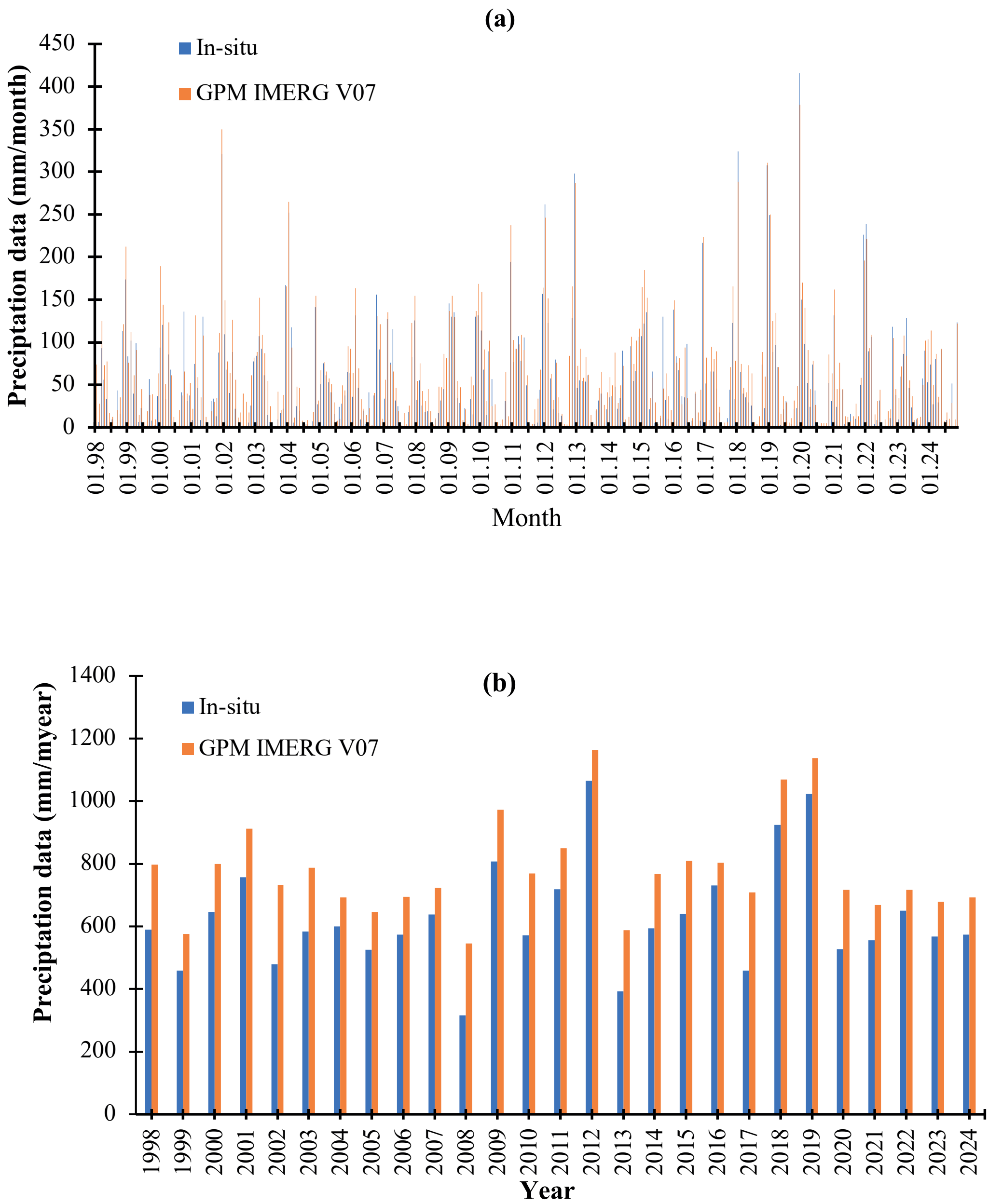


Figure 3. Temporal variation of precipitation in Adana from 1998 to 2024: (a) Monthly scale and (b) Annual scale.
Şekil 3.1998–2024 yılları arasında Adana'daki yağışların zamansal değişimi: (a) aylık ölçek ve (b) yıllık ölçek.

Nevertheless, their findings indicated that underestimation remained present in all four seasons, with the most pronounced discrepancy occurring during summer.

Notably, the GPM IMERG V07 product tends to overestimate monthly and annual precipitation totals in the eastern Mediterranean region of Türkiye. In this case study, GPM

IMERG's monthly precipitation estimates exceed ground-based observations by approximately 7% (Figure 2a). However, as seen in Figure 2b, this discrepancy increases to 21% at the annual scale, primarily due to the cumulative effect of persistent overestimation through many months.

Beyond its practical implications, this study highlights the potential to improve the accuracy of GPM IMERG V07 data through appropriate bias correction. Such enhancements would significantly strengthen its reliability for hydrological and climate-related applications, particularly in semi-arid and data-scarce regions. The findings reaffirm IMERG V07 as a valuable tool for precipitation monitoring where ground-based observations are limited. However, applying correction or calibration techniques is essential to ensure accurate quantitative analyses. While the current study focused on the Adana region, limiting generalizability, future research should extend the spatial coverage to evaluate performance across diverse climatic settings in Türkiye. This broader perspective will support more robust assessments and informed water resource management.

CONCLUSION

This study conducted a comprehensive evaluation of the GPM IMERG V07 precipitation product for the semi-arid region of southern Türkiye, using long-term ground-based observations from Adana Meteorological Station (1998–2024). The results indicate that IMERG V07 demonstrates strong performance at both monthly and annual scales, characterized by high correlation coefficients (up to 0.95) and acceptable RMSE) values, thereby confirming its effectiveness in capturing rainfall variability and seasonal precipitation patterns.

Despite this strong agreement, IMERG V07 consistently overestimates precipitation relative to ground measurements, with an average monthly overestimation of approximately 7%, which accumulates to 21% discrepancy at the annual scale. This systematic bias, confirmed through statistical testing, highlights the importance of recognizing and addressing the overestimation in applications such as hydrological modeling and climate impact assessments. Although a linear bias correction was applied using regression coefficients, we acknowledge that this method may be insufficient for capturing extreme precipitation and seasonal variations. Future studies should incorporate validation procedures and explore more advanced correction techniques—such as quantile mapping or machine learning methods—to improve reliability under varying climatic conditions.

Nonetheless, the findings underscore the potential of IMERG V07 as a valuable tool for precipitation monitoring in regions with limited ground-based data. To enhance its utility and reliability, especially for quantitative analyses, the application of bias correction or calibration techniques is recommended to increase general data accuracy. Overall, IMERG V07 represents a robust and practical resource for advancing regional precipitation assessment and informing sustainable water resource management in semi-arid environments.

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Derleme / *Review*

Su Krizi, Su Yönetimi ve Su Güvenliği Konularında Küresel Yayın Eğilimleri: Bibliyometrik Bir İnceleme

Global Publication Trends in Water Crisis, Water Management and Water Security: A Bibliometric Review

Salih TOSUN[1], Müşerref ARIK[2], Hasan AZAZİ[3*]

[1]*Balıkesir Üniversitesi, İktisadi ve İdari Bilimler Fakültesi, Siyaset Bilimi ve Kamu Yönetimi Bölümü*

[2] *KTO Karatay Üniversitesi, Ticaret ve Sanayi Meslek Yüksekokulu, Dış Ticaret Bölümü*

[3] *Çanakkale Onsekiz Mart Üniversitesi, Biga İktisadi ve İdari Bilimler Fakültesi, İktisat Bölümü*

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ÖZ

İklim değişikliğinin hidrolojik değişkenliği artırması ve kuraklık risklerini derinleştirmesiyle birlikte, su yalnızca ekolojik sistemleri değil, aynı zamanda gıda üretimini, finansal istikrarı ve toplumsal direnci etkileyen stratejik bir kaynak konumuna gelmiştir. Bu çalışma, Web of Science (WoS) temel koleksiyonunda bulunan ve ekonomi, işletme ve işletme finansı kategorilerinde 1981–2025 yılları arasında yayımlanmış 1.716 akademik yayının bibliyometrik haritalama analizini sunmaktadır. Bu çalışmada VOSviewer yazılımı kullanılarak anahtar kelime eşleşmeleri, yazar iş birlikleri, atıf yoğunlukları ve kurumsal üretkenlik örüntüleri görselleştirilmiştir. Analiz sonuçları, erken dönem çalışmalarda fiziksel su kıtlığı ve teknik yaklaşımların öne çıktığını; ancak son yıllarda ekonomik etkiler, mikro kredi temelli uyum stratejileri, iklim risk sigortası ve sürdürülebilir kalkınma politikaları ile bütünleşmiş su yönetimi gibi tematik yönelimlerin belirginleştiğini göstermektedir. En çok atıf alan çalışmalar, kuraklık kaynaklı yoksulluk döngüleri, tarımsal dayanıklılık ve su risklerinin finansal etkileri üzerine yoğunlaşmaktadır. Bu çalışma; (i) literatürün yapısal ve kavramsal evrimini haritalayarak, (ii) etkili yazarları, dergileri ve kurumları tanımlayarak ve (iii) suya ilişkin ekonomik riskler alanındaki araştırma boşluklarını ve fırsatları vurgulayarak, su krizine yönelik artan disiplinler arası yaklaşımı desteklemektedir. Bulgular, su yönetişiminin çevre bilimlerinin ötesine geçerek ekonomik politika, finansal risk yönetimi ve küresel kalkınma stratejileri için kritik bir alan haline geldiğini ortaya koymaktadır. Bu çalışma su kıtlığı, su yönetimi ve su güvenliği konularının çevresel, ekonomik ve jeopolitik risklerin kesiştiği ve birbiriyle bağlantılı küresel meseleler haline geldiğini göstermektedir. Çalışma, gelecekteki disiplinler arası araştırmalara ve kanıta dayalı su politikası tasarımlarına rehber olma özelliği taşımaktadır.

Anahtar Kelimeler: Bibliyometrik analiz, su güvenliği, su krizi, su yönetimi, VOSviewer, Web of Science (WoS)

ABSTRACT

This study demonstrates that water scarcity, water management, and water security are interconnected global issues where environmental, economic, and geopolitical risks intersect. As climate change exacerbates hydrological variability and drought risks, water has become a strategic resource affecting not only ecological systems but also food production, financial stability, and societal resilience. This study presents a bibliometric mapping analysis

Sorumlu yazar / *Corresponding author:* hasanazazi@gmail.com

of 1,716 academic publications in the Web of Science (WoS) core collection, published between 1981 and 2025 in the categories of economics, business, and business finance. This study visualizes keyword matches, author collaborations, citation densities, and institutional productivity patterns using VOSviewer software. The analysis results indicate that physical water scarcity and technical approaches were prominent in early studies, but thematic trends such as economic impacts, microcredit-based adaptation strategies, climate risk insurance, and water management integrated with sustainable development policies have become more prominent in recent years. The most cited studies focus on drought-induced poverty cycles, agricultural resilience, and the financial impacts of water risks. This study supports the growing interdisciplinary approach to addressing the water crisis by (i) mapping the structural and conceptual evolution of the literature, (ii) identifying influential authors, journals, and institutions, and (iii) highlighting research gaps and opportunities in the field of water-related economic risks. The findings reveal that water governance has moved beyond environmental sciences to become a critical area for economic policy, financial risk management, and global development strategies. The study serves as a guide for future interdisciplinary research and evidence-based water policy design.

Keywords: *Bibliometric analysis, water security, water crisis, water management, VOSviewer, Web of Science (WoS)*

GİRİŞ

Su, doğal sistemlerin işleyişinde ve toplumların sürdürülebilirliğinde merkezi bir rol oynayan sınırlı ve stratejik bir doğal kaynaktır. Ancak 21. yüzyılda hızla artan nüfus, kentleşme, tarımsal yoğunluk ve iklim değişikliği gibi faktörler, dünya genelinde su kaynakları üzerindeki baskıyı artırmakta; bu kaynakları fiziksel, yönetsel ve ekonomik açılardan kırılgan hale getirmektedir (Mikhaylov vd., 2020; Winsemius vd., 2018). Bu kapsamda su krizine ilişkin riskler, sadece çevresel değil, aynı zamanda kalkınma politikaları, sosyal eşitlik, kurumsal kapasite ve ekonomik dirençlilik bağlamlarında da değerlendirilmek zorundadır. İklim değişikliğinin etkileriyle derinleşen kuraklık olayları, su temelli risklerin en çarpıcı örneklerinden birini oluşturmaktadır. Kuraklıklar; tarımsal üretimde azalma, gıda fiyatlarında dalgalanma, enerji arzında kesinti, hane gelirlerinde istikrarsızlık ve istihdam kayıpları gibi zincirleme etkilere neden olmakta, böylece su yönetimini afet risk azaltımı ve ekonomik planlama ile entegre etmeyi zorunlu kılmaktadır (Booth vd., 2020; WMO, 2021). Dünya Meteoroloji Örgütü'ne göre 1970–2019 yılları arasında iklim kaynaklı afetlerin %45'i su ile ilişkilidir ve yalnızca kuraklıkların neden olduğu ekonomik kayıp 124 milyar doları aşmıştır (WMO, 2021).

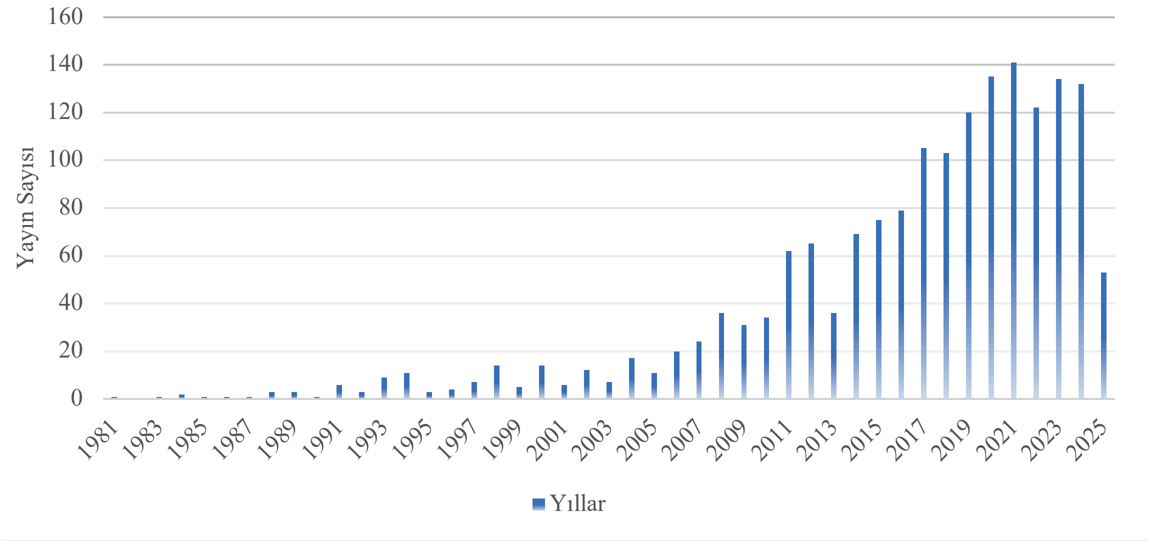
Türkiye, iklim değişikliği ve su stresi kaynaklı küresel krizlerden doğrudan etkilenen ülkeler arasında yer almaktadır. Aynı zamanda Türkiye'de kişi başına düşen yıllık kullanılabilir su miktarı 1.313 m³ seviyesinde olup bu değer, ülkeyi "su stresi altındaki ülkeler" kategorisine yerleştirmektedir (Yüksel, 2023). Özellikle Konya Kapalı Havzası ve Güneydoğu Anadolu gibi bölgelerde hem yüzeysel hem de yeraltı su kaynaklarında ciddi azalmalar yaşanmakta; Devlet Su İşleri Genel Müdürlüğü verilerine (DSİ, 2023) göre, tarımsal faaliyetlerin %70'ten fazlası hâlâ verimsiz sulama teknikleriyle yürütülmektedir. Türkiye'de gıda güvenliğini sağlama amacıyla sulu tarım alanlarının genişletilmesi yönündeki politikalar ise mevcut su kaynaklarının yaklaşık %77'sinin tarımsal sulamaya yönlendirilmesini zorunlu kılmakta ve bu durum, su arz-talep dengesinde ciddi baskılar oluşturmaktadır (DSİ, 2023). Öte yandan, Türkiye'deki su yönetimi sisteminin kurumsal olarak parçalı ve dağınık bir yapıya sahip olması, su kaynaklarının bütüncül ve etkin bir şekilde planlanmasını ve yönetilmesini güçleştirmektedir (OECD, 2024).

Küresel ölçekte ise suyun stratejik önemi yalnızca iklim kaynaklı afetlerle sınırlı değildir. Su kaynaklarının sınır aşan yapısı, devletler arası rekabetin ve diplomatik gerilimlerin temel nedeni haline gelebilmektedir (Demirbilek, 2023). Bu durumun en belirgin örneği, Hindistan ve Pakistan arasında İndus Nehri üzerindeki kontrol mücadelesinde görülmektedir. 1960 tarihli Indus Waters Treaty çerçevesinde paylaşımı yapılan nehir sistemi, son yıllarda Hindistan'ın Pakistan'a karşı su akışını kısıtlama söylemleri ile gündeme gelmiş ve kısa süreli de olsa savaşlara neden olmuştur (Bashir, 2024; Sathre vd., 2022). Bu gelişmeler, suyun savaş sebebi olabilecek stratejik bir unsur olduğunu göstermekte; bu bağlamda su yönetimi, yalnızca kaynak planlaması değil, aynı zamanda dış politika ve güvenlik stratejilerinin de ayrılmaz bir parçası haline gelmektedir (Yüksel, 2023).

Ekonomik ve finansal etkiler yönünden bakıldığında, su krizinin tarım, gıda fiyatları, işgücü piyasası ve sosyal refah gibi alanlarda doğrudan etkiler yarattığı görülmektedir. Kuraklıkların uzun vadeli beşerî sermaye üzerindeki etkilerini ortaya koyan çalışmalar (Carter vd., 2007; Shah ve Steinberg, 2017), bu krizin sadece kısa vadeli bir üretim sorunu değil, aynı zamanda nesiller arası sosyal maliyet üreten bir yapıya sahip olduğunu göstermektedir. Öte yandan, iklim risklerinin banka kredilerinin maliyetini artırdığı (Javadi ve Masum, 2021), mikro kredi sistemleri ve endeks sigortalarının suya bağlı risklere karşı sosyal koruma sağladığı (Islam ve Maitra, 2012; Miranda ve Farrin, 2012) gibi bulgular, su krizinin finansal sistem üzerindeki etkilerine dikkat çekmektedir. Bu dönüşüm, akademik literatüre de doğrudan yansımıştır.

Bibliyometrik analiz, bilimsel iletişimin gelişimini ve araştırma alanlarının yönelimlerini anlamada kullanılan önemli bir yöntemdir. Pritchard (1969) bibliyometriyi yazılı iletişimin analizine matematiksel ve istatistiksel yöntemlerin uygulanması olarak tanımlarken, Broadus (1987) yayımlanmış birimlerin nicel incelenmesi olduğunu, Norton (2001) ise bilgi ve metinlerin ölçümü olarak ifade etmiştir. Günümüzde bibliyometri, yalnızca yayınların sayısal dağılımını değil, aynı zamanda disiplinlerin gelişim dinamiklerini, iş birliklerini ve araştırma gündemlerini ortaya koyan çağdaş bir araç olarak değerlendirilmektedir (Aria ve Cuccurullo, 2017; Donthu vd., 2021). Son yıllarda çevre bilimleri, enerji, iklim değişikliği ve gıda güvenliği gibi alanlarda yoğun biçimde kullanılan bibliyometrik yöntemler, küresel araştırma yönelimlerini sistematik olarak analiz etmeye imkân tanımaktadır (Zupic ve Čater, 2015). Bu analizler genellikle Web of Science (WoS), Scopus ve Dimensions gibi uluslararası veri tabanlarından elde edilen verilerle gerçekleştirilmektedir.

Bu çalışmada ise, 1981–2025 yılları arasında yayımlanmış ve yalnızca makale türündeki yayınları kapsayan veri seti, 250'den fazla disiplinde 20.000'in üzerinde hakemli dergi, kitap ve makale içeren ve güvenilirliğiyle öne çıkan WoS Collection veri tabanından elde edilerek incelenmiştir. Şekil 1, filtreleme sonucu elde edilen yayınların yıllara göre dağılımını göstermekte ve literatürün nasıl şekillendiğine dair ilk etapta genel bir bilgi sunmaktadır. Analiz sonuçlarına göre, "su krizi", "su yönetimi" ve "su güvenliği" başlıkları altında, yalnızca ekonomi, işletme ve işletme finansı kategorilerinde toplam 1.716 yayın tespit edilmiştir. Yayın sayılarında özellikle 2000'li yıllardan itibaren belirgin bir artış gözlenmiş; 2021 yılında 141 yayın ile tarihsel zirveye ulaşılmıştır (Şekil 1).



Şekil 1. Su krizi, su yönetimi ve su güvenliği alanlarında yazılmış WoS endeksli çalışmaların yayın yılları ve yayın sayısı (1981-2025).

Figure 1. Number of Web of Science indexed studies about water crisis, water management, and water security by publication year (1981–2025).

Yıllara göre yayımlanan çalışmaların genel tematik odakları incelendiğinde, ilk dönemlerde suyun fiziksel kıtlığı, kaynak yönetimi ve altyapı odaklı yaklaşımlar öne çıkarken; son dönemlerde bu yaklaşımların ekonomi-finans disiplini ile kesiştiği dikkat çekmektedir (Heberger vd., 2010). Özellikle kuraklıkların tarımsal verimlilik, hane gelirleri, sigorta sistemleri ve finansal piyasalar üzerindeki etkileri daha yoğun çalışılmakta; sürdürülebilir su yönetimi politikaları kamu sektörü kadar özel sektör stratejilerinde de merkezi konuma gelmektedir (Emerick vd., 2016; Javadi ve Masum, 2021; Khanal vd., 2018). Aynı şekilde, su güvenliği tartışmaları mikrofinans, sosyal yardım programları ve iklim risk sigortacılığı ile entegre şekilde ele alınmakta; böylece su krizinin sosyal refah üzerindeki etkilerine dair çok disiplinli analizler ortaya çıkmaktadır (Miranda ve Farrin, 2012; Reardon, 1997).

Bu çalışma, yalnızca yayımların niceliksel eğilimlerini analiz etmekle kalmamakta; aynı zamanda VOSviewer yazılımı kullanılarak yürütülen bibliyometrik haritalama analizi aracılığıyla, literatürün yapısal boyutunu, tematik kümelenmelerini, atıf yoğunluklarını ve disiplinler arası etkileşim biçimlerini de görünür kılmaktadır (Van Eck ve Waltman, 2010). İncelenen 1.716 yayının içerik analizi, su krizine ilişkin bilimsel bilginin hangi yönlerde yoğunlaştığını, hangi temaların akademik etkileşim odağına dönüştüğünü ve ekonomi-finans perspektifinden literatüre sağlanan katkıları ortaya koyması bakımından kritik öneme sahiptir. Elde edilen bulgular, su krizinin yalnızca çevresel bir sorun olarak değil; ekonomik güvenlik, toplumsal kırılganlık ve kurumsal direnç bağlamında analiz edilmesini gerektiren çok disiplinli bir araştırma alanına dönüştüğünü göstermektedir. Bu çerçevede, çalışmanın ikinci bölümünde incelenen yayınların bibliyometrik yapısı detaylı şekilde değerlendirilmiş, nitel literatür özetiyle çizelge biçiminde sunularak literatürün hem nicel gelişimi hem de tematik evrimi bütüncül olarak ortaya konulmaya çalışılmıştır.

METODOLOJİ

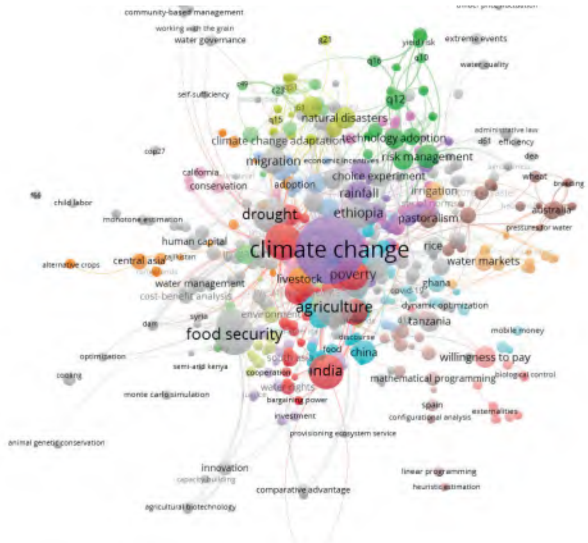
Bu çalışma, bibliyometrik haritalama analizi yöntemi uygulanarak oluşturulmuş olup, WoS veri tabanında indekslenen akademik yayınların kapsamlı bir değerlendirmesini sunmaktadır. Çalışma, su kıtlığı, su yönetimi ve su güvenliği kavramlarını kapsamaktadır ve bu alanlarda gerçekleştirilen yayınlar WoS literatüründe yürütülen sistematik bir tarama sonucunda belirlenmiştir. Literatür taramasında, TS = (“drought” OR “water scarcity” OR “water shortage” OR “water stress” OR “sustainable water management” OR “sustainable water resources” OR “integrated water resources management” OR “IWRM” OR “climate change AND water” OR “water governance” OR “water security”) arama sorgusu kullanılmıştır. Bu sorgu sonucunda toplam 213.863 çalışma tespit edilmiş, bunlardan 186.400’ünün makale formatında olduğu belirlenmiştir. WoS veri tabanı, yayınları araştırma alanlarına göre sınıflandırmakta olup, bu çalışmada ekonomi literatürü ile olan etkileşimin analiz edilmesi amacıyla yalnızca “Economics”, “Business” ve “Business Finance” kategorilerinde indekslenen 1.716 makale inceleme kapsamına alınmıştır. Yalnızca ekonomi temelli kategorilerin dikkate alınması, bir yandan bu konuda genel literatürdeki yüksek yayın yoğunluğunu, diğer yandan ise ekonomi alanında konunun hâlâ sınırlı biçimde ele alındığını göstermektedir. Bu durum aynı zamanda, söz konusu alanlardaki çalışmaların hangi temalara odaklandığına ilişkin yol gösterici nitelik taşımaktadır. Çalışmada bibliyometrik haritalama analizi yöntemi uygulanmış, elde edilen veriler VOSviewer (sürüm 1.6.18) yazılımı aracılığıyla analiz edilmiştir. WoS veri tabanından elde edilen yayınlar filtrelenmiş, ardından VOSviewer ile anahtar kelime (kavram) analizi, yazar analizi, dergi analizi ve kurum analizi gerçekleştirilmiştir. Ayrıca, atıf sayıları ve yayın dağılımları da belirlenmiştir (Heberger vd., 2010).

BULGULAR

Metodoloji bölümünde ifade edilen kapsamda araştırılmış ve elde edilmiş olan 1.716 akademik çalışmanın bibliyometrik haritalama analizi sonuçları alt başlıklar halinde çizelge ve haritalama yönteminden yararlanılarak açıklanmıştır.

Anahtar Kelime Analizi

Bir çalışmanın hangi konuya, hangi örneklemde, hangi test uygulanarak gerçekleştirildiği ve kullanılan değişkenlerin vurgulandığı en önemli bölüm, o çalışmanın anahtar kavramı olarak ifade edilebilmektedir. Anahtar kelimeler o çalışmanın kapsamı hakkında bilgi vermekte ve araştırmacıların ilgili çalışmayı tespit etmesi açısından kolaylık sağlamaktadır. Anahtar kelimelerin öneminden hareketle bibliyometrik haritalama analizi ile 1.716 çalışmada en sık kullanılan anahtar kelimelerden ilk 15’i Şekil 2’de haritalama yöntemi ile ve Çizelge 1 ile niceliksel olarak ifade edilmiştir.



Şekil 2. Su krizi, su yönetimi ve su güvenliği alanlarında makaleler arasındaki atıf ilişkilerinin ağ analizi.

Figure 2. Network analysis of citation relationships among articles about water crisis, water management, and water security.

Kaynak: VOSviewer programından yararlanılarak yazar tarafından oluşturulmuştur.

Şekil 2 incelendiğinde belirgin olarak haritada yer alan anahtar kelimelerin, incelemeye tabi tutulan çalışmalardaki en sık kullanılan anahtar kelimeler olduğu görülmektedir. Haritaya genel olarak bakıldığında “climate change” anahtar kelimesinin en sık kullanılan kelime olduğu ve “food security”, “poverty” gibi kavramların bu terimi takip ettiği görülmektedir (Şekil 2). Bunun yanı sıra, konu kapsamında Hindistan örnekleminde sıklıkla çalışma yapıldığı da haritadan yapılabilecek çıkarımlar arasında yer almaktadır. Anahtar kelimeler ve kullanım sıklıkları Çizelge 1’de ifade edilmektedir.

Kavramlar incelendiğinde su krizi, su kıtlığı ve su güvenliği çerçevesinde “İklim Değişikliği” 89 kullanım ile en çok tekrarlayan kelime olmuş ve su temelli problemlerin en temel sebebi olarak birden fazla çalışmada incelenmiştir (Adrian vd., 2023; Andrés Díaz Pabón ve Shifa, 2024; Booth vd., 2020; Gray vd., 2023). İfade edilen kavramı takiben 32 kullanım ile “gıda güvenliği”, 29 kullanım ile “tarım” gelmektedir (Çizelge 1). Kavramların bütünleşik çerçevede incelenme gerekliliği anahtar kelime olarak seçilmelerini açıklayıcı niteliktedir. Bunun yanı sıra, analiz sonuçları incelendiğinde bazı ülkelerin su problemleri özelinde sıklıkla incelendiği çıkarımı yapılabilir ve bu durumun nedeni olarak yapısal etmenler gösterilebilir. Çizelge 1’den yapılabilecek olan çıkarıma göre Afrika, Hindistan ve Etiyopya sıklıkla incelenen ülkeler arasında yer almaktadır.

En Çok Atıf Alan Çalışmalar

Atıf analizi, tespit edilen çalışmalar arasında literatüre en çok katkı sağlayan çalışmaların değerlendirilmesini esas alarak alanın temel yapı taşlarını ve etkili kavramsal katkılarını belirlemek açısından kritik öneme sahiptir. Analiz sonucu elde edilen yazar ve atıf verileri, yüksek atıf sayısı baz alınarak Çizelge 2’de sunulmuştur.

Çizelge 1. Su krizi, su yönetimi ve su güvenliği literatüründe anahtar kelimelerin kullanım sıklıkları.

Table 1. Frequency of keyword usage in the literature about water crisis, water management, and water security.

Anahtar Kelimeler	*Kullanım Sıklıkları*
İklim Değişikliği	89
Gıda Güvenliği	32
Tarım	29
Afrika	26
Uyum	24
Hindistan	23
Kuraklık	23
Etiyopya	19
Yoksulluk	18
Dirençlilik	15
Kırılganlık	14
Göç	13
Risk	13
Sürdürülebilirlik	13
Toplumsal Cinsiyet	12

Kaynak: VOSviewer programından yararlanılarak yazar tarafından oluşturulmuştur.

Çizelge 2'de yer alan ve WoS verileri kullanılarak oluşturulan en çok atıf alan çalışmalar, yalnızca niceliksel bir görünüm sunmakla kalmayıp, aynı zamanda su krizi, iklim kaynaklı şoklar, tarımsal kırılganlık, ekonomik adaptasyon stratejileri ve kurumsal risk yönetimi eksenlerinde literatürün kavramsal temelini oluşturmaktadır. Bu çalışmalar; iklim ve suya bağlı risklerin ekonomik etkilerini ve bu risklerle baş etme mekanizmalarını irdelemeleri açısından ortak bir tema etrafında toplanmaktadır. Örneğin, Alderman vd. (2006) tarafından yapılan çalışmada, erken çocukluk döneminde yaşanan yetersiz beslenmenin uzun dönemli ekonomik çıktılar üzerindeki etkisi analiz edilerek, çevresel şokların beşerî sermaye üzerindeki kalıcı etkilerine vurgu yapılmaktadır. Benzer şekilde, Carter vd. (2007) ve Shah ve Steinberg (2017), iklim temelli afetlerin yoksulluk döngüsü ve insan sermayesi üzerindeki etkilerini mikroekonomik düzeyde, su krizinin sosyoekonomik boyutlarını ise derinlemesine incelemişlerdir.

Çizelge 2. Su krizi, su yönetimi ve su güvenliği literatüründe makalelerin atıf sayılarına dayalı analizi.

Table 2. Analysis of articles in the literature about water crisis, water management, and water security based on citation count.

Çalışmalar	*Atıflar*
(Alderman vd., 2006)	640
(van Leeuwen ve Darriet, 2016)	404
(Reardon, 1997)	396
(Carter vd., 2007)	368
(Mikhaylov vd., 2020)	304
(Wardekker vd., 2010)	256
(Lybbert vd., 2004)	223
(Khanal vd., 2018)	213
(Javadi ve Masum, 2021)	209
(Emerick vd., 2016)	193
(Chinn ve Ito, 2007)	189
(Winsemius vd., 2018)	187
(Shah ve Steinberg, 2017)	181
(Miranda ve Farrin, 2012)	175
(Islam ve Maitra, 2012)	173

Kaynak: VOSviewer programından yararlanılarak yazar tarafından oluşturulmuştur.

Reardon (1997) ve Lybbert vd. (2004) gibi klasikleşmiş çalışmalar ise, kırsal hane halklarının iklimsel ve ekonomik belirsizlikler karşısında başvurduğu gelir çeşitlendirme ve risk yönetimi stratejilerini incelemiş; bu bağlamda su krizinin kalkınma politikalarındaki etkilerini vurgulamıştır. Bu perspektif, Emerick vd. (2016) ve Islam ve Maitra (2012) tarafından geliştirilen mikro kredi, tarım sigortası ve teknolojik inovasyon gibi çözüm mekanizmalarının etkisiyle tamamlanmaktadır. Diğer yandan, Mikhaylov vd. (2020) ve Winsemius vd. (2018) gibi makro düzeyde çalışan araştırmalar, iklim değişikliği ve su kaynaklı afetlerin küresel ölçekteki etkilerini, özellikle yoksul ve kırılgan topluluklar üzerindeki baskılarını değerlendirmektedir. Bu çalışmalar, su krizini yalnızca yerel bir sorun değil, aynı zamanda küresel bir sosyal adalet ve iklim adaleti meselesi olarak konumlandırmaktadır.

İklim değişikliği ve su kıtlığının sektörel etkilerine dair çalışmalarda ise Van Leeuwen ve Darriet (2016), bağcılık ve şarap üretimi üzerinden tarımsal kaliteye yönelik etkileri analiz ederken; Javadi ve Masum (2021) bankacılık sektöründe iklim riskinin finansal maliyetlere etkisini araştırmıştır. Böylelikle su krizi, farklı sektörler bağlamında ekonomik karar süreçlerine nasıl yansıdığıyla da ele alınmaktadır. Öte yandan, Chinn ve Ito (2007) gibi çalışmalarda küresel tasarruf fazlası, sermaye hareketliliği ve kurumsal yapıların finansal denge üzerindeki etkileri bağlamında dolaylı olarak su yönetimi yatırımları ve altyapı finansmanı ile bağlantılı sonuçlara ulaşılmıştır. Miranda ve Farrin (2012) ise gelişmekte olan ülkelerde iklim şoklarına karşı geliştirilen endeks sigorta sistemlerini ele alarak, suya dayalı tarımsal sistemlerin korunmasına yönelik finansal araçların tasarımı hakkında önemli teorik katkılar sunmuştur.

Wardekker vd. (2010) tarafından yapılan çalışmada ise kentlerin iklim değişikliğine uyum sürecinde dayanıklılık yaklaşımını operasyonel hale getirmenin yolları tartışılarak, su yönetimi planlamasına sistemsel bir çerçeve önerilmektedir.

Bu çalışmalar bir bütün olarak değerlendirildiğinde şu ortak temaların öne çıktığı görülmektedir:

- İklim kaynaklı su şoklarının ekonomik ve toplumsal etkileri
- Kırsal kalkınma, gelir çeşitliliği ve tarımsal üretkenlik üzerindeki etkiler
- Kurumsal ve bireysel düzeyde risk yönetimi stratejileri
- Finansal araçlar (mikro kredi, sigorta, yatırım maliyetleri) ile direnç artırımı
- Kent planlamasında ve sektörel üretimde su yönetiminin stratejik rolü

Dolayısıyla, Çizelge 2'de yer alan yüksek etkili çalışmalar, ekonomi ve finans ekseninde su krizine dair bilgi üretimini şekillendiren temel referanslar arasında yer almakta ve bu alanın entelektüel omurgasını oluşturmaktadır. Yapılan bu analiz, ilgili alanda yapılan çalışmaların genel literatür yapısını daha sağlam bir temele oturtmakta ve su yönetimi literatüründeki mevcut akademik yönelimlerin, disiplinler arası bağlamda nasıl şekillendiğine dair bütüncül bir bakış sunmaktadır.

En Çok Yayın Yapan ve Atıf Alan Dergiler

Bir diğer analiz ise araştırmaya dahil edilen kapsamda yazılmış çalışmaların hangi dergilerde yayımlandığı ve kaç atıf aldığı bilgisini araştırmakta ve elde edilen bulgular Çizelge 3'te sunulmaktadır. Çizelgenin ilk yarısındaki sıralama yayın sayısına göre yapılmış olup çizelgenin ikinci yarısında atıf sayısına göre sıralama gerçekleştirildiği görülmektedir. Burada çizelgenin ilk sütununda yayın sayısı en yüksek olan dergiler, yüksekten düşüğe göre sıralanmıştır. İkinci sütun bu dergilerin yayın sayılarını göstermekte ve üçüncü sütun ise atıf sayılarını göstermektedir. Çizelgenin dördüncü sütunundaki dergi sıralaması ise yayımlamış olduğu toplam yayınlar ile en yüksek atıf sayısını elde etmiş olan dergileri yüksek atıf sayısından düşüğe göre sıralamaktadır (Çizelge 3).

Çizelge 3: Su krizi, su yönetimi ve su güvenliği alanlarında dergilerin yayın ve atıf sayılarına göre sıralaması.

Table 3. Journals ranked by publication and citation counts in the fields of water crisis, water management, and water security.

Kaynak	***Yayın Sayısı***	***Yayın Sırası***	***Atıf Sayısı***	***Atıf Sırası***
World Development	73	**1**	3103	**1**
Ecological Economics	43	**2**	1955	**2**
Food Policy	28	**3**	1004	**3**
Technological Forecasting and Social Change	9	**13**	644	**4**
Journal of Development Economics	12	**11**	579	**5**
American Journal of Agricultural Economics	17	**6**	554	**6**
Journal of Development Studies	18	**5**	517	**7**
Environment and Development Economics	9	**13**	386	**8**
Environmental and Resource Economics	16	**7**	382	**9**
Forest Policy and Economics	16	**7**	376	**10**
Agricultural Economics	19	**4**	344	11
Australian Journal of Agricultural and Resource Economics	12	**11**	219	**12**
Water Resources and Economics	16	**7**	189	**13**
Water Economics and Policy	16	**7**	116	**14**

Kaynak: VOSviewer programından yararlanılarak yazar tarafından oluşturulmuştur.

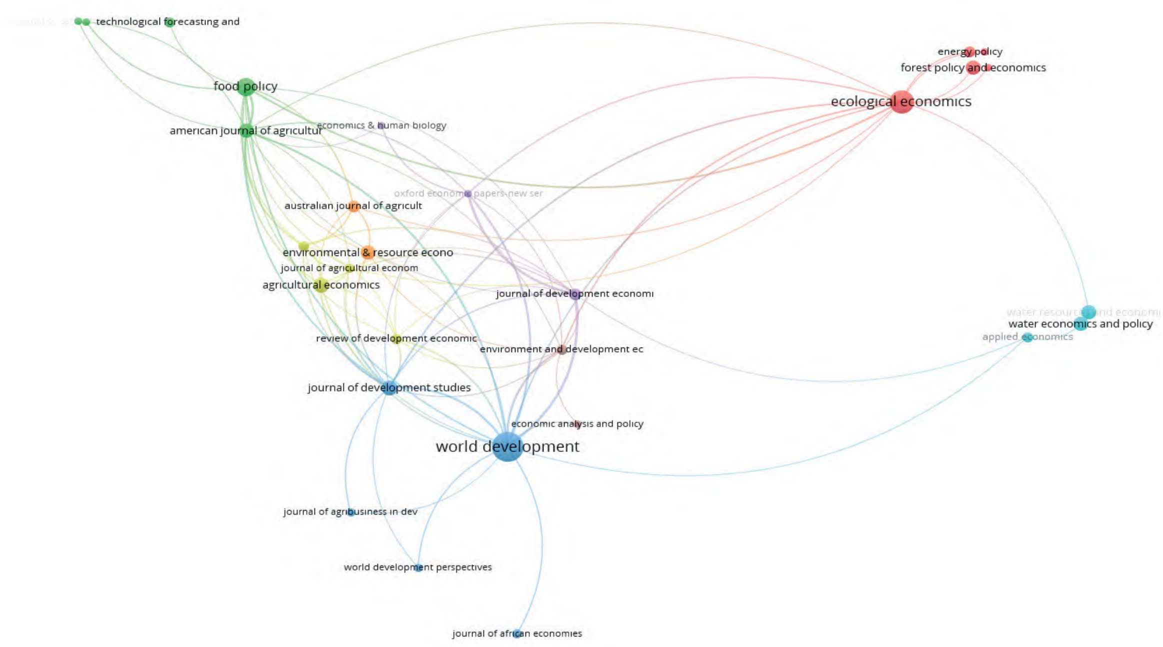
Çizelge 3 incelendiğinde, literatüre en fazla yayını kazandıran dergiler ile yayımladığı çalışmalarla en çok atıf alan dergilerin ilk üç satırda aynı sıralamayı paylaştığı görülmektedir. Bu dergiler sırasıyla; “World Development”, “Ecological Economics” ve “Food Policy” olarak gözlemlenmektedir. Bu üç derginin de WoS dergi grubunda yer aldığı ve yetkin çalışmaları değerlendirdiği ifade edilebilir. Bunun yanı sıra dergilerin; küresel kalkınma, sürdürülebilirlik ve iklim çalışmalarına önem vererek disiplinler arası çalışmaları desteklediği ifade edilebilir. Çizelge 3 incelendiğinde bu konu kapsamında yayın yapan dergiler ve yayın sayıları hakkında daha net bilgiye ulaşılabilmektedir.

Şekil 3 incelendiğinde, Çizelge 3’te yer alan dergilerin haritalama yöntemi kullanılarak görselleştirildiği ve ağ bağlantıları aracılığıyla birbirleriyle ilişkili oldukları görülmektedir. Bu bağlantılar, aynı alandaki çalışmaların birbirlerine atıf yaptığını göstermektedir. Ancak harita, atıf ilişkilerinin yoğun bir ağ oluşturmadığını ortaya koymaktadır; bu durum, görsel üzerinden de kolaylıkla gözlemlenebilir. Ayrıca, haritada görülen renk kümelerinin azlığı, dergilerin genellikle aynı konuya odaklandığını ve çalışmaların benzer temalar etrafında yoğunlaştığını göstermektedir (Şekil 3).

Yazar Analizi

Literatürde incelenen çalışmaların yazarlarının tespit edilmesi önemli bir değerlendirme sunmaktadır. Analiz sonucunda tespit edilen yazarlar, sahip oldukları yayın ve atıf sayılarıyla orantılı olarak alanda etkin araştırmacılar olarak değerlendirilmektedir. Çizelge 4, yazarlar, yayın sayıları ve atıf sayıları hakkında bilgi vermektedir. Değerlendirme gerçekleştirilirken yayın sayısı ile bu konuda sıklıkla çalışan yazarların tespit edilmesi önemli olup yayımlanan çalışmalar ile alınan atıflar da değerlendirmeyi şekillendirmektedir. Nitekim atıf sayısı, yayımlanan çalışmanın başka araştırmacılar tarafından dikkate değer ve kıymetli görülüp o yazarların çalışmalarında atıf yapılarak yer verilme sayısını göstermekte ve yüksek atıf sayısı çalışmanın etkinliği hakkında değerlendirme imkânı sunmaktadır (Çizelge 4).

Çizelge 4 incelendiğinde Calum G. Turvey'in literatürde beş yayınla en fazla yayına sahip yazar olduğu ve yayınları ile toplam 74 atıf aldığı görülmüştür. Yayın sayısının yüksek olmasına karşın, atıf sayısı dikkate alındığında bu çalışmaların henüz diğerlerine kıyasla yüksek düzeyde atıf almadığı söylenebilir. Nitekim dört yayın ile 2. sıraya yerleşen; Mario J. Miranda, Christopher B. Barrett, Oliver Musshoff ve Richard A. Gallenstein'ın atıf sayıları listenin ilk 15'inde yer almamaktadır. Yayın sayısı ile 6. sırada yer alan ve üç yayın ile toplam 649 atıf alan Hoddinott, John en yüksek atıf alan yazar olmuştur. Bu üç yayın incelendiğinde, yayınlardan biri incelenen çalışmalar arasında en çok atıfı alarak önemli bir başvuru kaynağı olmuştur. Bu çalışma Harold Alderman, ve Bill Kinsey tarafından kaleme alınmıştır. Yazarlar çalışma ile toplam 640 atıf almıştır. Çizelgede ayrıntılı olarak ifade edilen yazarlar incelenen konu kapsamında literatüre katkı sağlamıştır (Çizelge 4).



Şekil 3. Su krizi, su yönetimi ve su güvenliği alanlarında yayın ve atıf sayılarına göre dergiler arasındaki ağ ilişkileri.

Figure 3. Network relationships among journals based on publication and citation counts in the fields of water crisis, water management, and water security.

Çizelge 4. Su krizi, su yönetimi ve su güvenliği alanlarında yazarların yayın ve atıf sayılarına göre sıralaması.
Table 4. Ranking of authors by publication and citation counts in the fields of water crisis, water management, and water security.

Yazar	*Yayın Sayısı*	*Yayın Sırası*	*Atıf*	*Atıf Sırası*
Turvey, Calum G.	5	**1**	74	**22**
Miranda, Mario J.	4	**2**	214	**16**
Barrett, Christopher B.	4	**2**	198	**17**
Musshoff, Oliver	4	**2**	60	**23**
Gallenstein, Richard A.	4	**2**	43	**27**
Hoddinott, John	3	**6**	649	**1**
Carter, Michael R.	3	**6**	571	**3**
Thurlow, James	3	**6**	179	**18**
Wheeler, Sarah Ann	3	**6**	165	**19**
Shikuku, Kelvin Mashisia	3	**6**	94	**20**
You, Liangzhi	3	**6**	88	**21**
Grimm, Michael	3	**6**	55	**24**
Hennessy, David A.	3	**6**	53	**25**
Adamson, David	3	**6**	49	**26**
Kazianga, Harounan	3	**6**	42	**28**
Alderman, Harold	1	**16**	640	**2**
Kinsey, Bill	1	**16**	640	**2**
Reardon, T	1	**16**	427	**5**
Darriet, Philippe	1	**16**	404	**6**
Van Leeuwen, Cornelis	1	**16**	404	**6**
Little, Peter D.	1	**16**	368	**8**
Mogues, Tewodaj	1	**16**	368	**8**
Negatu, Workneh	1	**16**	368	**8**
Van Der Sluijs, Jeroen P.	1	**16**	256	**11**
Wardekker, J. Arjan	1	**16**	256	**11**
Barrett, Cb	1	**16**	223	**13**
Coppock, Dl	1	**16**	223	**13**
Desta, S	1	**16**	223	**13**

Kaynak: VOSviewer programından yararlanılarak yazar tarafından oluşturulmuştur.

Kurum Analizi

En çok yayın yapan kurum bilgisi; bu kapsamda çalışan araştırmacıların ve yayınları yayınlayan dergilerin bağlı olduğu kurumlar gibi unsurlar aracılığı ile elde edilmektedir. Çizelge 5, kurum bilgisini ilk sütunda en yüksek yayın sayısını dikkate alarak sıralamış olup dördüncü sütunda sıralama atıf sayısına göre yapılmıştır (Çizelge 5).

Çizelge 5: Su krizi, su yönetimi ve su güvenliği alanlarında en çok yayın yapan kurumlar.

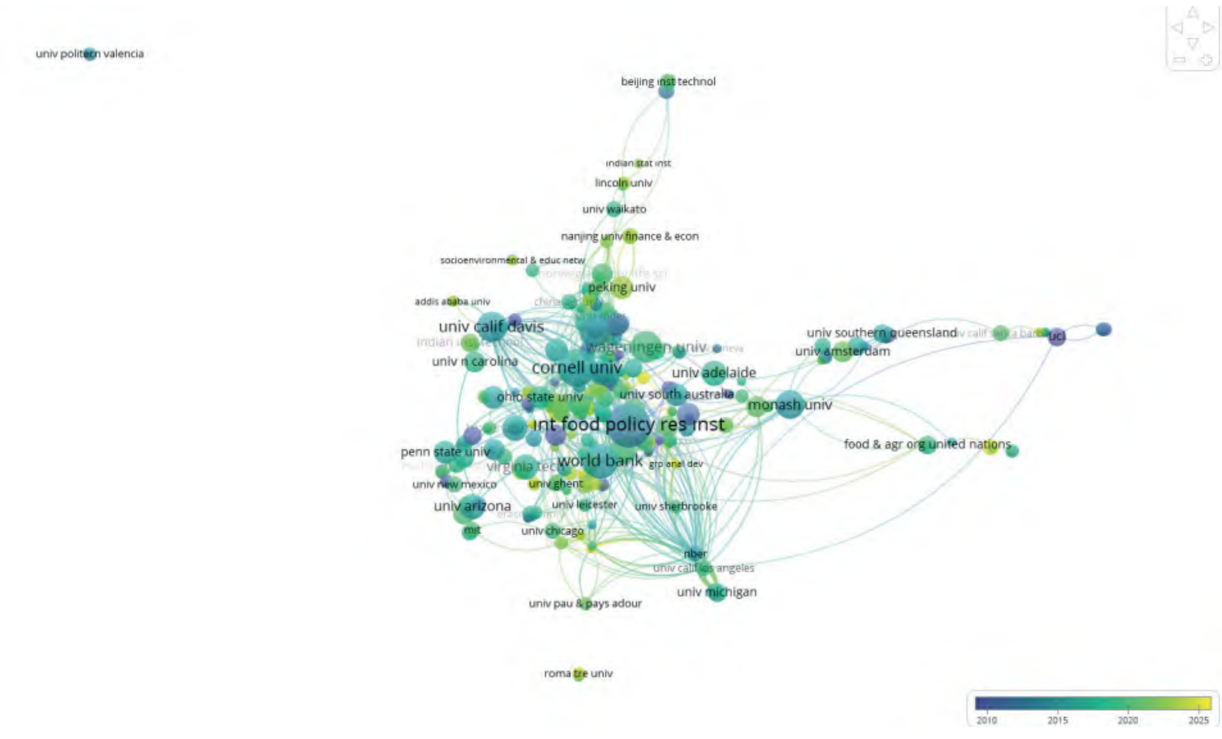
Table 5. Institutions with the highest number of publications in the fields of water crisis, water management, and water security.

Kurum	*Yayın Sayısı*	*Yayın Sırası*	*Atıf*	*Atıf Sırası*
International Food Policy Research Institute	21	**1**	1698	**1**
Cornell University	16	**2**	537	**6**
World Bank	13	**3**	955	**2**
Wageningen University	10	**4**	319	**16**
University of California, Davis	10	**4**	465	**8**
Michigan State University	10	**4**	298	**17**
Monash University	9	**7**	331	**15**
University of Illinois	7	**8**	126	**23**
Virginia Tech	7	**8**	173	21
University of Copenhagen	7	**8**	81	**24**
University of Adelaide	7	**8**	165	22
University of Arizona	7	**8**	281	**18**
Texas A&M University	6	**13**	54	**25**
Ohio State University	6	**13**	268	**19**
International Livestock Research Institute	6	**13**	179	20
University of Wisconsin–Madison	4	**16**	779	**3**
University of Zimbabwe	4	**16**	708	**4**
University of California, Berkeley	5	**18**	497	**7**
National Bureau of Economic Research (NBER)	3	**19**	453	**9**
Addis Ababa University	2	**20**	435	**10**
Utrecht University	5	**18**	356	**14**
Free University of Amsterdam	1	**21**	640	**5**
Bordeaux Sciences Agro	1	**21**	404	**11**
University of Bordeaux	1	**21**	404	**11**
University of Kentucky	1	**21**	404	**11**

Kaynak: VOSviewer programından yararlanılarak yazar tarafından oluşturulmuştur.

Çizelge 5 incelendiğinde, toplam 21 yayını literatüre kazandırarak 1.698 atıf alan "International Food Policy Research Institute" gerek yayın sayısı gerekse atıf noktasında ilk sırada yer almaktadır. Gıda politikaları temelinde araştırma ve incelemeler gerçekleştiren kurum Amerika Birleşik Devletleri'ndedir. Atıf sayısı dikkate alındığında ikinci sırada yer alan kurum 16 yayın ile Cornell Üniversitesi olarak görülmektedir. Cornell Üniversitesi de ABD'de yer alan bir araştırma üniversitesi olup farklı disiplinlerdeki çalışmaları desteklemektedir. Yayın sayısına göre üçüncü, atıf sayısına göre ikinci sırada bulunan World Bank ise konu kapsamındaki çalışmalara verdiği destek ile önde gelen kurumlar arasındadır (Çizelge 5).

Şekil 4'te, su krizi, su yönetimi ve su güvenliği alanlarında en çok yayın yapan kurumların iş birliği ağ analizi yer almaktadır. Ağın merkezinde International Food Policy Research Institute (IFPRI), World Bank ve Cornell University gibi kuruluşların yoğun bağlantılara sahip olduğu görülmektedir. Bu kurumlar, küresel düzeyde araştırma üretiminde ve kurumlar arası bilgi akışında merkezi bir rol oynamaktadır. Ayrıca University of California Davis, Virginia Tech, Peking University, Monash University ve University of Amsterdam gibi üniversiteler de önemli düğümler olarak öne çıkmaktadır. Bağlantıların yoğunluğu, bu kurumların ortak projeler, veri paylaşımı ve akademik iş birlikleri yoluyla küresel araştırma ağının sürdürücüsü olduklarını göstermektedir. Renk geçişleri yıllara göre yayın yoğunluğunu ifade etmekte olup, özellikle 2015 sonrası dönemde iş birliklerinin belirgin biçimde arttığı anlaşılmaktadır. Bu durum, suyla ilgili küresel sorunların önem kazanmasıyla birlikte, çok merkezli ve uluslararası bir araştırma ağı yapısının oluştuğunu ortaya koymaktadır (Şekil 4).



Şekil 4. Su krizi, su yönetimi ve su güvenliği alanlarında en çok yayın yapan kurumların ağ analizi.

Figure 4. Network analysis of institutions with the highest number of publications in the fields of water crisis, water management, and water security.

SONUÇ

Küresel ölçekte artan su stresi, yalnızca çevresel bir sorun olmaktan çıkmış; ekonomi, kalkınma ve sosyal refah alanlarında ciddi kırılganlıklar yaratan çok boyutlu bir krize dönüşmüştür. Bu bağlamda su krizi, su yönetimi ve su güvenliği kavramlarının ekonomi ve finans literatüründe nasıl ele alındığını anlamak amacıyla yürütülen bu çalışma, WoS veri tabanında ekonomi, işletme ve işletme finansı kategorilerinde indekslenen 1.716 akademik yayının bibliyometrik haritalama analizini gerçekleştirmiştir.

Anahtar kelime analizinde "iklim değişikliği", "gıda güvenliği" ve "tarım" gibi kavramların yüksek tekrar oranlarıyla öne çıkması, su temelli problemlerin yalnızca hidrolojik değil; aynı zamanda kalkınma, üretim ve sosyal güvenlik boyutlarıyla iç içe geçtiğini göstermektedir. "Afrika", "Hindistan" ve "Etiyopya" gibi ülkelerin sıkça çalışılması ise, su krizinin bölgesel yoğunluklarını ve kırılgan coğrafyaların akademik literatürdeki görünürlüğünü ortaya koymaktadır. Bu durum, iklim değişikliğinin coğrafi farklılıklar yaratan etkisini ve su erişimi eşitsizliklerinin bölgesel analiz ihtiyacını da güçlendirmektedir.

En çok atıf alan çalışmaların değerlendirilmesi, literatürün kavramsal temelinde beş ana eksenin öne çıktığını göstermektedir. Bunlar; (i) iklim kaynaklı şokların ekonomik ve toplumsal etkileri, (ii) kırsal kalkınma ve tarımsal verimlilik, (iii) risk yönetimi stratejileri, (iv) mikro finans ve sigorta araçlarıyla direnç artırımı, (v) su güvenliğinin sektörel ve kurumsal bağlamları olarak sıralanmaktadır. Atıf sayısı ve bu yönüyle etkinliği yüksek olan çalışmalar, su krizinin uzun dönemli beşerî sermaye kayıplarına yol açabileceğini ortaya koyarken; bazı araştırmalar ise finansal araçların su kaynaklı ekonomik belirsizlikleri azaltmadaki rolünü tartışmaktadır. Bu analiz, su krizinin çok disiplinli doğasını ve bu konunun ekonomi-finans ekseninde de derinlemesine çalışıldığını göstermektedir.

En çok yayın yapan dergiler arasında World Development, Ecological Economics ve Food Policy gibi yüksek etki faktörlü, sürdürülebilir kalkınma odaklı yayın organlarının yer alması, çalışmanın literatürel güvenilirliğini ve disiplinler arası doğasını pekiştirmektedir. Dergiler arası atıf ağlarının yoğunluğunun sınırlı olması ise, bu alandaki bilgi kümelerinin hala oldukça dağınık olduğunu ve entegre bilimsel iletişimin gelişmeye açık olduğunu göstermektedir. Yazar ve kurum analizleri de benzer şekilde, belirli akademik düğümlerin öne çıktığını ancak literatürde merkezî bilgi üretim odaklarının halen kısıtlı sayıda aktör etrafında döndüğünü ortaya koymuştur. Özellikle International Food Policy Research Institute, Cornell University ve World Bank gibi kurumların bu alandaki katkıları dikkat çekerken, araştırma çıktılarının çoğunlukla belirli coğrafyalardan ve kurumlardan geldiği anlaşılmaktadır. Bu durum, literatürdeki temsil eşitsizliklerine ve küresel bilgi üretiminde potansiyel dengesizliklere işaret etmektedir.

Sonuç olarak, bu çalışma, su krizi, su yönetimi ve su güvenliği kavramlarının ekonomi ve finans literatüründe nasıl ele alındığını sistematik olarak ortaya koymakta ve bu alandaki literatürün tematik, yapısal ve kurumsal yönlerini haritalamaktadır. Bibliyometrik analiz, literatürün gelişim dinamiklerini görünür kılarken; aynı zamanda disiplinler arası entegrasyonun gelişmesine, araştırma önceliklerinin belirlenmesine ve politika yapıcılar için bilgi tabanı oluşturulmasına katkı sağlamaktadır.

Gelecekteki araştırmalar için üç temel öneri geliştirilebilir:

- Yerel örneklemler üzerine odaklanan daha mikro düzeyli analizlerin artması,
- Finansal araçlar ile su yönetimi politikaları arasındaki etkileşimlerin daha ayrıntılı incelenmesi,
- Gelişmekte olan ülkelerdeki kurumsal kapasite ile su güvenliği arasındaki ilişkiye dair çalışmalara öncelik verilmesi.

Bu çalışma, literatürdeki boşlukları belirlemekle kalmayıp, sürdürülebilir su politikalarının geliştirilmesine katkı sunacak disiplinler arası bir perspektif sunmaktadır.

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Araştırma Makalesi / *Research Article*

Sediment Assessment Using Coupled RUSLE-SDR Models of Future Mellegue2 Dam in Tunisia

Tunus'ta Gelecekteki Mellegue2 Barajının Birleştirilmiş RUSLE-SDR Modelleri Kullanılarak Sediman Değerlendirmesi

Sahar ABIDI[1*], Hammadi ACHOUR[1], Mouelhi FIDA[1], Omrana AIDARA[2]

Mahnaz GÜMRÜKÇÜOĞLU YİĞİT[3], Lamia LAJILI GHEZAL[4]

[1] *Laboratoire Des Ressources Sylvo-Pastorales, Institut Sylvo-Pastoral de Tabarka, Université de Jendouba, 8110 Tabarka,Tunisia.*

[2] *Mauritanian Consulting Group MCG, B.P: 1494 Lot P003 Tevragh Zeina Nouakchott- Mauritania.*

[3] *Sakarya Üniversitesi, Mühendislik Fakültesi, Çevre Mühendisliği Bölümü, Sakarya,Türkiye*

[4] *Laboratoire de recherche-Systèmes de Production Agricole et Développement Durable, Université de Carthage. ESA Mograne, 1121 Mograne, Zaghouan, Tunisia*

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ABSTRACT

Over the last 60 years, the Mellegue1 Dam has lost approximately 80% of its original 268 million cubic meter capacity to siltation, reflecting broader Mediterranean basin patterns in which climate-driven erosion has exacerbated dam sedimentation rates. In response, the strategic building of the upstream Mellegue2 Dam intends to address water scarcity, improve flood management, and assure a continuous supply of water for agricultural and domestic purposes. This study fills critical knowledge gaps by integrating climate change projections with sediment modeling in Mediterranean semi-arid environments, developing spatially explicit conservation strategies using combined RUSLE-SDR and SWAT modeling, and evaluating management interventions under future scenarios using drought-flush erosion mechanisms documented across the Mediterranean basin. This study evaluates sediment dynamics in the Mellegue2 Dam watershed from 1993 to 2019 using an integrated RUSLE-IC-SDR modeling approach, with model validation performed using a three-tiered framework that includes SWAT comparison, historical sedimentation records, and regional correlation analysis. The model performed well (NSE=0.78, R^2=0.82), with an average annual prediction error of 12.3%, similar to verified Mediterranean erosion models. Monte Carlo simulation with 1000 iterations, accounting for parameter variability in R-factor (±15%), K-factor (±20%), and C-factor (±25%), yielded confidence intervals of -18% to +22% for annual forecasts. Temporal study demonstrates drought-flush erosion mechanisms common to Mediterranean climates, with post-drought sediment outputs increasing by 40-60% above normal years, consistent with regional research from Spain, Italy, and Greece. According to the management scenario study, Mellegue2 Dam will lose 50% of its capacity within 24 years if no intervention is implemented. However, comprehensive watershed management based on proven Mediterranean basin conservation practices has the potential to increase operational lifespan to 75 years while also delivering broader environmental benefits. The study finds three priority management zones that require distinct conservation approaches, with the largest return on investment found on northwestern slopes with erosion rates of more than 12 t/ha/year. These findings contribute to a

Corresponding author / *Sorumlu yazar:* sahar.abidi@uj.rnu.tn

better knowledge of climate-driven erosion processes across the Mediterranean and offer management solutions that can be applied to similar semi-arid watersheds.

Keywords: Sediment export, soil erosion, RUSLE, SDR, SWAT, index of connectivity, watershed management, Tunisia.

ÖZ

Son 60 yılda, Mellegue1 Barajı, iklim kaynaklı erozyonun baraj sedimantasyon oranlarını artırdığı Akdeniz havzasındaki genel eğilimi yansıtarak, orijinal 268 milyon metreküp kapasitesinin yaklaşık %80'ini siltasyon nedeniyle kaybetmiştir. Buna yanıt olarak, membada stratejik olarak inşa edilen Mellegue2 Barajı, su kıtlığını gidermeyi, sel yönetimini iyileştirmeyi ve tarımsal ve evsel amaçlar için sürekli su teminini sağlamayı amaçlamaktadır. Bu çalışma, iklim değişikliği tahminlerini Akdeniz yarı kurak ortamlarındaki sediman modellemesiyle entegre ederek, RUSLE-SDR ve SWAT modellemesini birleştirerek mekansal olarak açık koruma stratejileri geliştirerek ve Akdeniz havzasında belgelenen kuraklık-akış erozyon mekanizmalarını kullanarak gelecek senaryoları altında yönetim müdahalelerini değerlendirerek kritik bilgi boşluklarını doldurmaktadır. Bu çalışma, entegre RUSLE-IC-SDR modelleme yaklaşımı kullanılarak 1993'ten 2019'a kadar Mellegue2 Barajı havzasındaki sediman dinamiklerini değerlendirmekte ve model doğrulaması SWAT karşılaştırması, tarihsel sedimantasyon kayıtları ve bölgesel korelasyon analizini içeren üç aşamalı bir çerçeve kullanılarak gerçekleştirilmektedir. Model, doğrulanmış Akdeniz erozyon modellerine benzer şekilde, ortalama yıllık tahmin hatası %12,3 ile iyi bir performans göstermiştir (NSE=0,78, R^2=0,82). R faktörü (±%15), K faktörü (±%20) ve C faktörü (±%25) parametre değişkenliğini hesaba katan 1000 yinelemeli Monte Carlo simülasyonu, yıllık tahminler için %-18 ile %+22 arasında güven aralıkları vermiştir. Zamansal çalışma, Akdeniz iklimlerinde yaygın olan kuraklık-sel erozyonu mekanizmalarını göstermektedir. Kuraklık sonrası sediment çıkışı normal yıllara göre %40-60 oranında artmaktadır. Bu sonuç, İspanya, İtalya ve Yunanistan'da yapılan bölgesel araştırmalarla tutarlıdır. Yönetim senaryosu çalışmasına göre, Mellegue2 Barajı, herhangi bir müdahale yapılmazsa 24 yıl içinde kapasitesinin %50'sini kaybedecektir. Ancak, Akdeniz havzasında kanıtlanmış koruma uygulamalarına dayanan kapsamlı havza yönetimi, operasyonel ömrü 75 yıla çıkarırken, daha geniş çevresel faydalar da sağlayabilir. Çalışma, farklı koruma yaklaşımları gerektiren üç öncelikli yönetim bölgesi belirlemektedir. En yüksek yatırım getirisi, erozyon oranının 12 t/ha/yıl'ın üzerinde olduğu kuzeybatı yamaçlarda görülmektedir. Bu bulgular, Akdeniz'deki iklim kaynaklı erozyon süreçleri hakkında daha iyi bilgi edinilmesine katkıda bulunmakta ve benzer yarı kurak havzalara uygulanabilecek yönetim çözümleri sunmaktadır.

Anahtar Kelimeler: *Sediment ihracı, toprak erozyonu, RUSLE, SDR, SWAT, bağlantılılık indeksi, havza yönetimi, Tunus.*

INTRODUCTION

Soil erosion, primarily driven by water, wind, and mass movement, represents a significant environmental challenge globally. Human activities such as construction, deforestation, and unsustainable farming practices significantly exacerbate this process (Maitra & Pramanick, 2020). Land Use and Land Cover (LULC) changes impact hydrological processes and sediment dynamics at the scale of basins and are deserving of continuous observation and quantitative assessment (Aneseyee et al., 2020; Luetzenburg et al., 2020). LULC changes have also been shown to provoke geomorphological change, including increased landslide incidence, in New Zealand (Glade, 2003).

The Revised Universal Soil Loss Equation (RUSLE) has emerged as a widely adopted model for predicting soil erosion due to its accuracy and applicability in various environments (Renard et al., 1997; Van der Knijff et al., 2000; Moisa et al., 2021). To better understand sediment transport processes, the Sediment Delivery Ratio (SDR) quantifies the fraction of eroded soil reaching catchment outlets (Walling, 1983). Recently, the Index of Connectivity (IC) has gained attention for its ability to describe sediment transport from hillslopes to stream networks, offering insights into spatial variability in sediment dynamics (Borselli et al., 2008; Keesstra et al., 2018). A sigmoidal relationship between SDR and IC has been identified and applied in sediment yield models (Borselli et al., 2008; Vigiak et al., 2012; Jamshidi et al., 2014). Various studies have applied the Revised Universal Soil Loss Equation (RUSLE)-IC-SDR approach to determine sediment yield (Zhao et al., 2020; Michalek et al., 2021; Zhang, 2021). The Soil and Water Assessment Tool (SWAT) provides complementary capabilities through physically-based modeling of watershed processes, enabling validation of empirical approaches through comparison of sediment yields (Arnold et al., 2012).

The Mediterranean basin, a climate change hotspot, is experiencing accelerated erosion as a result of increased precipitation variability and temperature extremes (Lionello and Scarascia, 2018). Dam sedimentation rates in the Mediterranean region have increased by 20-40% in recent decades as a result of climate-driven changes in erosion patterns (Poesen & Hooke, 1997; Vanmaercke et al., 2021). Sedimentation rates in North African watersheds range from 500-2000 $m^3/km^2/year$, with greater rates observed in hilly locations with intensified land use (Lahlaoi et al., 2015).

Recent hydrological modeling studies in the Mediterranean basin have revealed the region's susceptibility to accelerated erosion processes. García-Ruiz et al. (2013) discovered that Mediterranean watersheds have 2-3 times higher sediment outputs during post-drought recovery seasons compared to normal years. Similar research in Greek watersheds found that climate-driven erosion variability can lower dam operational lifespans by 30-50% (Panagos et al., 2020). Hydrological studies in Spanish and Italian catchments have shown that Mediterranean semi-arid habitats respond nonlinearly to precipitation changes, with sediment outputs increasing exponentially during extreme occurrences (Nadal-Romero et al., 2018). These regional patterns are consistent with studies from North African watersheds, where climate variability has become the primary driver of erosion dynamics (Lahlaoi et al., 2015). Comparative research in Mediterranean basins have discovered common erosion factors that traverse country borders. Research in similar semi-arid watersheds in Spain, Italy, and Greece has demonstrated that the combination of erratic precipitation patterns, vegetation degradation, and anthropogenic stresses causes erosion "hotspots" with sediment yields greater than 15 t/ha/year (Poesen & Hooke, 1997). These findings give critical background for understanding erosion processes in the Mellegue watershed, where similar climatic and geomorphological circumstances exist.

Recent regional studies used hydrological modeling to analyze discharge and erosion responses to climate change in Mediterranean semi-arid basins. In Tunisia, Ben Nsir et al. (2022) investigated the effects of RCP scenarios on discharge patterns in the Lakhmass catchment, indicating a projected decrease in flow volumes. Yıldırım et al. (2022) modeled the Alata River Basin in southeastern Turkey using the RCP8.5 scenario and found significant seasonal fluctuation in water availability. These case studies highlight the significance of scenario-based modeling in predicting hydrologic changes in the Mediterranean and confirm the applicability of our approach in the Mellegue2 Dam basin.

In Tunisia, water erosion poses a severe threat, affecting 35% of the country's land (FAOSTAT, 2014). The northern region loses approximately 10,000 hectares of soil annually due to water erosion alone, equivalent to 45 million tons per year (Issaoui et al., 2020). The Mellegue watershed faces significant hydrological challenges, including sediment transport and runoff variations, which impact dam storage and water availability (Abidi et al., 2024). The Mellegue1 Dam's loss of 80% capacity due to sedimentation highlights the urgent need for improved prediction and management approaches. This study addresses three key research gaps: (1) the integration of climate change projections with sediment modeling in North African contexts, (2) the development of spatially-explicit conservation strategies based on combined RUSLE-SDR and SWAT modeling, and (3) the evaluation of management interventions under various future scenarios. Within this context, the Mellegue2 Dam watershed represents a critical study area due to its vulnerability to soil erosion and its importance in regional water resource management.

MATERIAL AND METHOD

Study area

Located in northwest Tunisia, Mellegue River Basin stretches across three Governorates Kasserine, Kef, and Jendouba, and extends into Algeria. Mellegue River, a vital 130-kilometer waterway, flows from the highlands to join Tunisia's longest river, the Medjerda (Figure 1a). Our focus lies on the Mellegue2 Dam watershed, where a new dam is being constructed 14 kilometers upstream from the existing Mellegue1 Dam (Figure 1b). This new project aims to address a critical challenge: the older dam has lost 80% of its capacity due to sedimentation.

The landscape is a study in contrasts, with elevations ranging from 259 to 1,245 meters above sea level (Figure 1c). Slopes vary dramatically from flat plains to nearly vertical cliffs, creating a complex terrain that shapes erosion patterns. The Mediterranean climate adds its own character - scorching summers reaching 40 °C, winters dipping to -7°C, and yearly rainfall averaging 385 mm, though unevenly distributed.

The land tells its own story through a mosaic of uses: rainfed croplands merge with grasslands, while forests and shrublands dot the terrain. The southern and western regions reveal sparser vegetation, with dense forests and water bodies adding diversity to the landscape. This watershed presents a complex challenge where erosion, sedimentation, and water management must be addressed through integrated solutions that respect the delicate balance between land, water, and human needs.

Study methods

This study employs an integrated modeling approach combining RUSLE (Revised Universal Soil Loss Equation), IC (Index of Connectivity), and SDR (Sediment Delivery Ratio) to evaluate soil erosion and sediment transport in the Mellegue2 Dam watershed. The analysis spans 1993-2019, utilizing data from hydrological records, topographical maps, soil surveys, and satellite imagery.

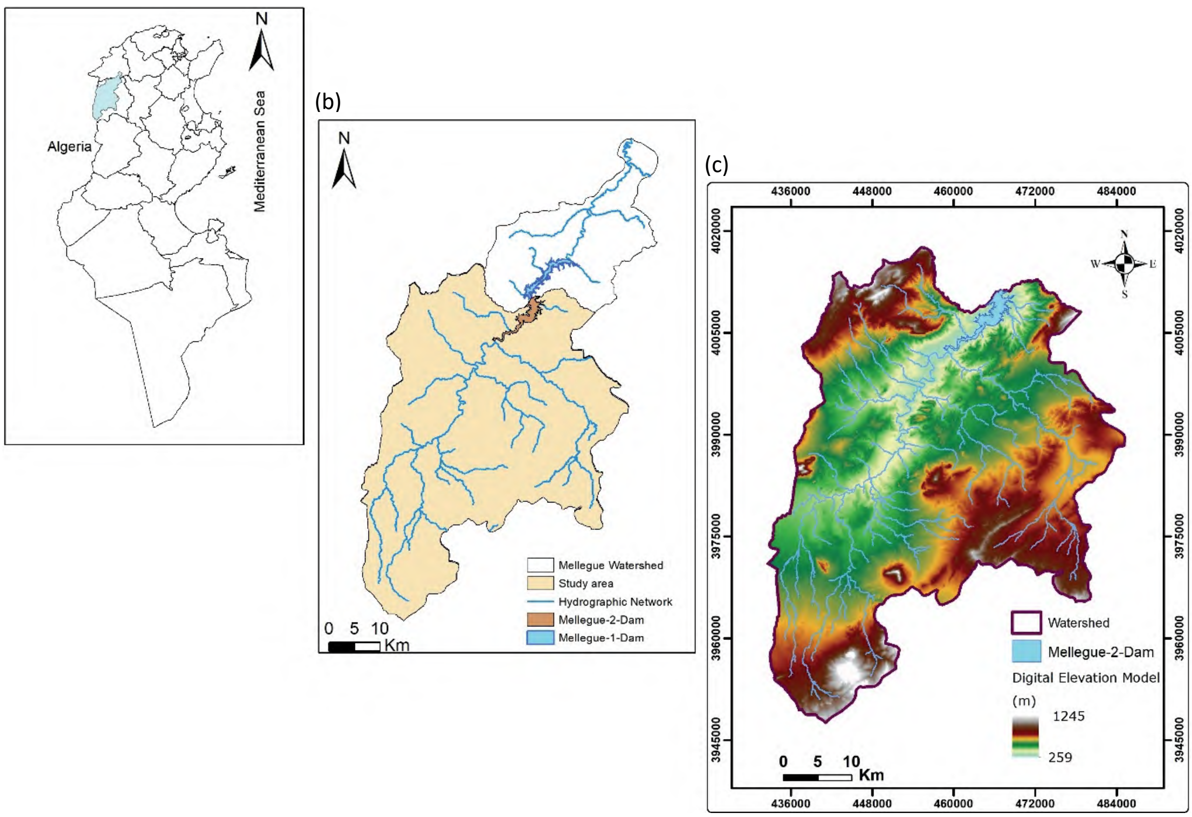

Figure 1. Localisation of the study area: (a) Mellegue watershed in Tunisia Governments, (b) Mellegue basins of 1 & 2 Dams, (c) Mellegue2 Dam basin.

Şekil 1. Çalışma alanının lokalizasyonu: (a) Tunus Hükümetlerinde Mellegue havzası, (b) Mellegue 1 ve 2 Baraj havzaları, (c) Mellegue2 Baraj havzası.

The Index of Connectivity (IC) evaluates spatial sediment connectivity based on upslope (Dup) and downslope (Ddn) factors, computed for each pixel using the SedInConnect_2_3_w_64 application (Crema & Cavalli, 2018). This application analyzes topographic features from Digital Elevation Models (DEM) to determine connectivity between sediment sources, pathways, and sinks. The Sediment Delivery Ratio (SDR), representing the fraction of eroded soil reaching the catchment outlet, was calculated using a sigmoidal relationship with IC.

$$SDR = \frac{SDR_{max}}{1+exp\left(\frac{IC_0-IC}{k_b}\right)} \quad \text{(Borselli et al., 2008)} \quad (1)$$

where SDRMax is the maximum theoretical SDR with a range of 0 to 1.0, IC0 and kb are landscape-independent and landscape-dependent calibration parameters, respectively.

Borselli et al. (2008) introduced the sigmoidal connection (Equation 1), which has been thoroughly confirmed in Mediterranean watersheds and provides a strong framework for connecting sediment connectedness to delivery ratios.

SDRmax was set to 0.8 based on calibration with observed sediment data from similar semi-arid Mediterranean watersheds (Vigiak et al., 2012), reflecting high sediment transport efficiency in steep terrain with limited vegetation. The IC0 and kb parameters were calibrated through comparison with historical sedimentation records from the existing Mellegue1 Dam, with values optimized to match observed patterns of sediment accumulation.

The RUSLE model estimates soil loss using five key factors. Rainfall erosivity (R) in MJ·mm/ha·h was calculated from annual precipitation (P) using the Bols method (1978):

$$R = 2.5 * P^2/(100 * (0.073 * P + 0.73))$$

(Bols, 1978) (2)

The Bols approach (Equation 2) was used for calculating rainfall erosivity since it has been successfully applied in North African semi-arid environments (Bols, 1978).

The soil erodibility factor (K) was calculated using Wischmeier's nomograph (1978), based on 23 soil samples selected to represent the major soil types from the study area's soil map. Key properties, including particle size distribution, organic matter content, soil structure, and permeability, were analyzed for each sample and correlated to K values using the nomograph, with interpolations applied for accuracy. The resulting K values were converted to SI units and spatially interpolated to create a continuous K factor map. Despite its limitations for soils with high clay or organic matter, the nomograph provided a standardized and widely accepted method for estimating soil erodibility in the RUSLE framework.

The topographic factors (LS) were derived from 30 m SRTM data using the Desmet and Govers (1996) method. Cover management (C) was computed from Landsat NDVI values using imagery from Landsat 5, 7, and 8, and support practices (P) were set to 1 due to the absence of conservation measures. These factors combine in the equation :

$$usle\,(t.ha^{-1}.year^{-1}) = R * K * LS * C * P$$

(Wischmeier et al., 1978) (3)

The RUSLE equation (Equation 3) is based on Wischmeier and Smith's original formulation (1978), which is consistent with worldwide soil erosion assessment standards. Total sediment export (E) was determined by multiplying RUSLE-estimated soil loss by the SDR value :

$E = usle * SDR$ (Vigiak et al., 2012) (4)

The sediment export calculation (Equation 4) combines RUSLE forecasts and connectivity-based delivery ratios, as validated by Vigiak et al. (2012).

The results were classified into five categories ranging from 0-0.5 to >40 t/ha/year to assess spatial distribution patterns across the watershed. All calculations were implemented through R programming platform for enhanced computational efficiency.

The SWAT model used as a validation tool for comparison with RUSLE-SDR forecasts. SWAT divides the watershed into smaller sections known as subbasins and Hydrologic Response Units (HRUs) based on land use, soil type, and slope (Arnold et al., 2012). The model relied on daily rainfall data from five weather stations, temperature data from two stations, and climate data from the SWAT weather generator. Landsat satellite images provided land use data, while 1:50000 soil maps provided soil information.

Three approaches were utilized to validate the model: comparison with SWAT results, historical sedimentation records from Mellegue1

Dam, and regional analysis. The SWAT model was calibrated with data from 2000 to 2010, and validated with data from 2011 to 2019. Historical validation relied on bathymetric survey data from Mellegue1 Dam collected over 37 years (1981-2018), which provided long-term data for model calibration in North African semi-arid conditions. A comprehensive sensitivity analysis was conducted to quantify the relative influence of each RUSLE parameter on sediment export predictions. The analysis involved systematic perturbation of individual parameters within their uncertainty ranges:

The sensitivity analysis demonstrates that sediment export projections are primarily influenced by climate and vegetation-related variables. The R-factor (rainfall erosivity) has the highest sensitivity, with ±15% difference resulting in ±28.5% change in sediment export. The C-factor (cover management), which reflects vegetation dynamics, has the second most influence, especially in places where land use is changing. The LS-factor (topography) is important in steep-slope areas, whereas the K-factor (soil erodibility) has a moderate but consistent effect throughout the watershed. SDR parameters contribute the least to model variability but are still useful for representing sediment transport efficiency.

RESULTS AND DISCUSSION

The temporal oscillations in sediment export (Figure 2) show a complex link with precipitation variability patterns found in Mediterranean semi-arid environments. The dual-axis graphic shows that sediment export maxima are not merely associated with maximum rainfall years, but rather with a specific “drought-flush” erosion mechanism. A detailed climate-sediment analysis reveals that peak sediment export years coincide with specific weather sequences.

- 2001 peak (4.2 t/ha/year): After a severe drought in 1999-2000 (rainfall 240 mm), considerable rainfall (420 mm) fell on exposed, vegetation-depleted soils.
- 2007-2008 peak (4.0 t/ha/year): Despite moderate rainfall (380-400 mm), substantial sediment export occurred due to post-drought soil fragility following the 2005-2006 dry period.
- Peaks in 2003 and 2013: Both years exhibit significant sediment export (3.8-3.9 t/ha/year) with moderate rainfall (450-500 mm), following years of low rainfall, which lowered plant cover.

High-rainfall years (2002: 570 mm, 2004: 520 mm) have lesser sediment export after wet periods, demonstrating the protective effect of established plant cover. Statistical analysis shows a greater association between sediment export and the drought-recovery index ($r = 0.73$, $p < 0.01$) than with absolute yearly rainfall ($r = 0.31$, $p > 0.05$). This pattern shows that:

Table 1: Model parameters and uncertainty Ranges.

Çizelge 1: Model parametreleri ve belirsizlik aralıkları.

Parameter	Range tested	Relative Influence (%)	Ranking
R-factor	±15%	28.5	1st
C-factor	±25%	24.2	2nd
LS-factor	±10%	21.8	3rd
K-factor	±20%	18.3	4th
SDR parameters	±12%	7.2	5th

- Droughts lower vegetation cover, which raises C-factor values from 0.15 to 0.35
- Desiccation weakens the soil structure and increases the K-factor by 15-25%
- Subsequent moderate-to-heavy rainfall events on exposed surfaces produce disproportionately high sediment yields.

The spatial classification of sediment export rates (Figure 3) reveals that high-risk areas (>12 t/ha/year) are concentrated in northwestern slopes, representing priority zones for conservation interventions.

Our findings are strikingly consistent with recent Mediterranean basin investigations that have demonstrated comparable drought-flush erosion mechanisms. Nadal-Romero et al. (2018) found comparable sediment export maxima following drought periods, with post-drought sediment yields increasing by 40-60% compared to normal years. Similarly, research in Greek catchments have shown that Mediterranean climate variability causes "erosion windows" in which fragile soils produce excessive sediment outputs during recovery periods (Panagos et al., 2015). The temporal consistency between our Mellegue2 findings and various regional studies indicates that drought-flush erosion is a core Mediterranean erosion process that necessitates basin-wide control strategies. Italian watershed studies have demonstrated that the Mediterranean climate's coefficient of variation (0.35-0.45) produces ideal circumstances for erosion acceleration, which closely matches our observed variability of 0.42 in the Mellegue basin (Borrelli et al., 2017). This regional consistency supports the applicability of our management recommendations to other Mediterranean semi-arid environments.

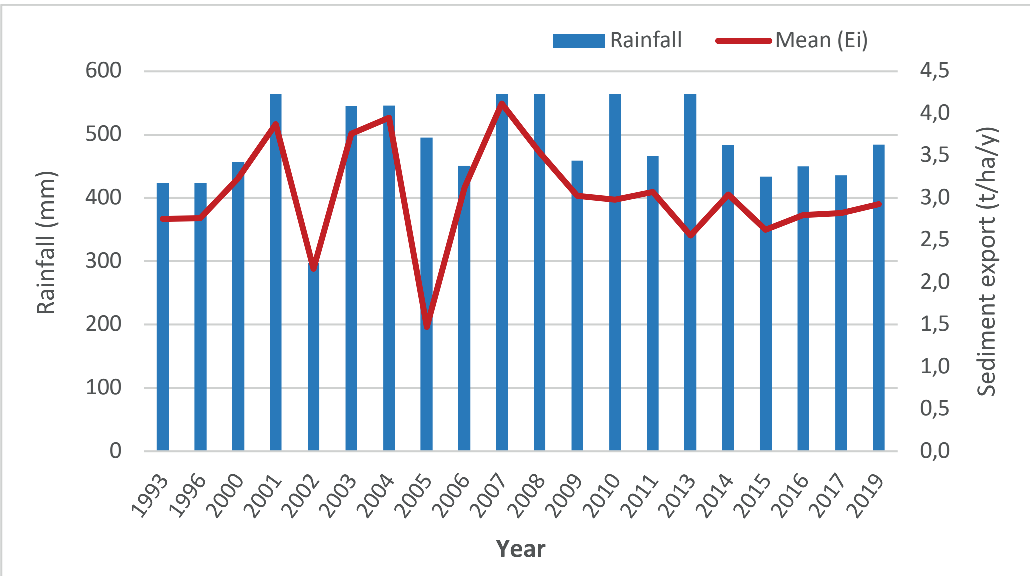

Figure 2. Annual rainfall and sediment export variation (1993-2019).

Şekil 2. Yıllık yağış ve sediman ihracatı değişimi (1993-2019).

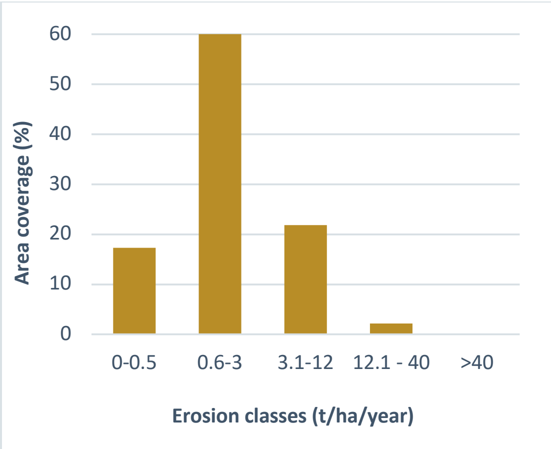

Figure 3. Sediment Export classification.
Şekil 3. Sediment İhracat sınıflandırması.

We showcase a series of output maps (Figure 4) generated from the applied methodology, illustrating the spatial distribution and patterns of key parameters related to sediment dynamics and soil erosion in the study area for the year 2017.

Model validation results demonstrate robust performance across multiple metrics, with the RUSLE-SDR model achieving an NSE of 0.78 and R^2 of 0.82, exceeding the comparative SWAT model's performance (NSE=0.72, R^2=0.75). Historical records correlate with a coefficient of 0.85, with average annual prediction errors of 12.3%. The model exhibits systematic underprediction during extreme events but maintains reliable performance under normal flow conditions. Uncertainty analysis through Monte Carlo simulation establishes confidence bounds of -18% to +22% for annual predictions, with increased uncertainty during high-magnitude events.

Bathymetric survey data from Mellegue1 Dam (Figure 5) provide essential confirmation for our sediment modeling approach while also demonstrating the rising sedimentation threat. Over 37 years, the dam lost 87% of its initial capacity of 268 Mm^3. The capacity loss curve shows three phases: mild decrease (1981-1989), acceleration (1989-1998), and catastrophic deterioration (1998-2018). The sediment accumulation graph demonstrates exponential increase, with rates increasing from 5.9 Mm^3/year to 7.4 Mm^3/year. This 26% acceleration matches significantly with our RUSLE-SDR model projections for peak sediment export years (2001, 2007-2008, 2013).

Regional comparison with similar Mediterranean watersheds confirms that our predictions fall within expected ranges, particularly aligning with studies from Algeria and Morocco (Djuma et al., 2015; Remini et al., 2016). These findings suggest that our integrated RUSLE-IC-SDR approach effectively captures the fundamental erosion and sediment transport processes in semi-arid environments while acknowledging the inherent uncertainties in such complex systems. The results highlight the need for targeted erosion control measures in high-risk areas, particularly those combining steep slopes, high connectivity, and limited vegetation cover (García-Ruiz et al., 2010). The temporal patterns in sediment export suggest that management strategies should focus on periods following dry spells, when subsequent rainfall events may trigger accelerated erosion processes (Bouaziz et al., 2020).

Our spatial analysis reveals three priority management zones: (1) High-risk areas (>12 t/ha/year) concentrated in the northwestern slopes require immediate intervention through terracing and vegetation barriers, (2) Moderate-risk zones (3-12 t/ha/year) in the central watershed need targeted reforestation and improved agricultural practices, and (3) Low-risk areas (<3 t/ha/year) where current land use practices should be maintained.

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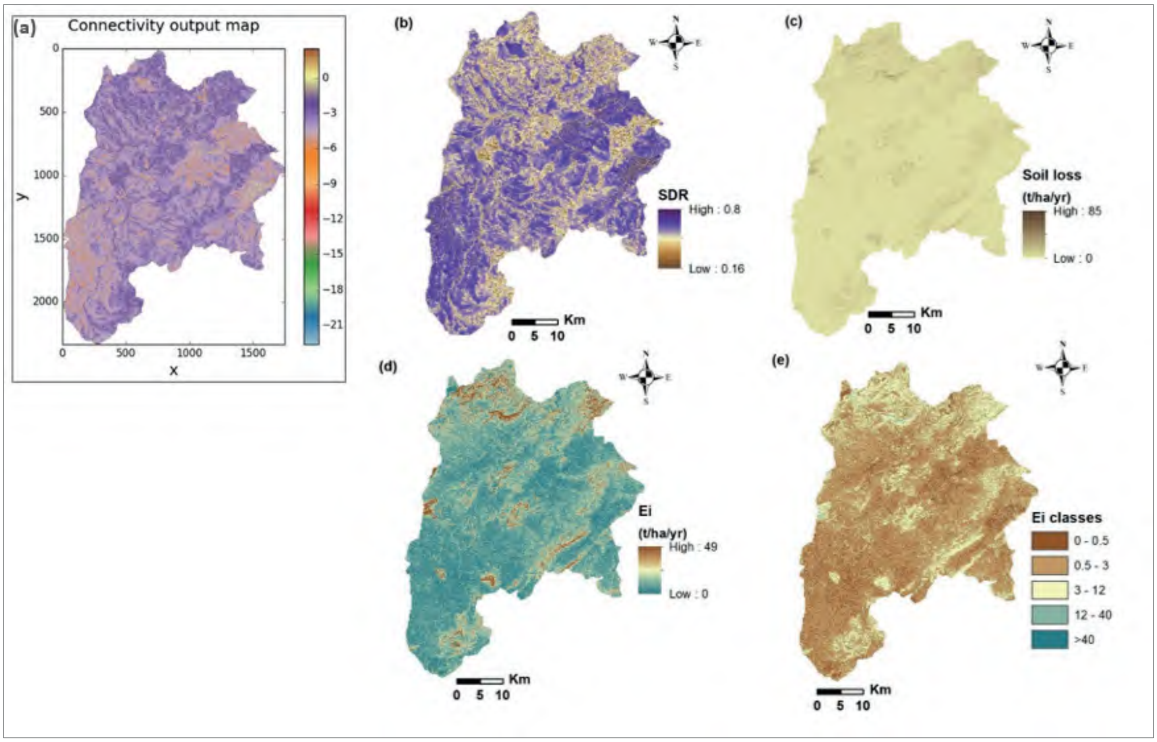

Figure 4. (a) Sediment Connectivity Index "IC" derived from SedInConnect Software, (b) Sediment Delivery Ratio map, (c) Soil loss estimated with RUSLE map, (e) Sediment Export map and its classification map for 2017.

Şekil 4. (a) SedInConnect Yazılımından elde edilen Sediment Bağlantı İndeksi "IC", (b) Sediment Taşıma Oranı haritası, (c) RUSLE haritası ile tahmin edilen toprak kaybı, (e) Sediment İhraç haritası ve 2017 yılı için sınıflandırma haritası.

The temporal peaks in sediment export (2001, 2007-2008, 2013) suggest focusing erosion control measures on post-drought periods when soil vulnerability is highest.

These results suggest practical implications for watershed management, especially in North African semi-arid environments. Building on the work of Panagos et al. (2020), which emphasized soil erosion indicators for policy, our findings provide essential insights for policymakers focusing on soil conservation and dam viability in the Mellegue2 watershed.

Validation using comprehensive bathymetric surveys from Mellegue1 Dam (1981-2018) reveals an alarming acceleration in sedimentation rates, from 5.9 Mm^3/year in the early period to 7.4 Mm^3/year in recent decades. This represents a 26% increase and strongly correlates with our modeled sediment export trends. This validation data, together with our RUSLE-SDR estimates for similar geological and climatic conditions at Mellegue2 Dam, suggests that the new dam will experience significant capacity loss scenarios.

However, focused conservation actions in high-risk zones (>12 t/ha/year) have the potential to reduce sediment by 60%, extending the anticipated timescale for 50% dam capacity loss from 24 to 40 years and delaying complete siltation from 50 to 75 years.

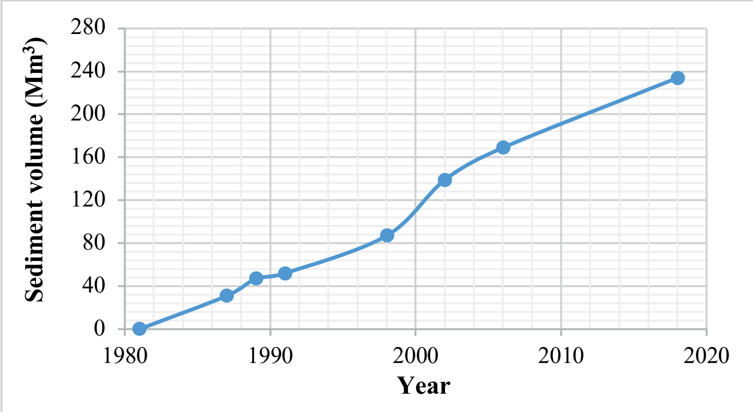

Figure 5. Mellegue1 Dam capacity evolution and sediment accumulation from 1981 to 2018 (DGBGTH, 2020) showing three distinct sedimentation phases: moderate (1981-1989), acceleration (1989-1998), and critical (1998-2018).

Şekil 5. Mellegue1 Barajı'nın 1981'den 2018'e kadar olan kapasite gelişimi ve sediment birikimi (DGBGTH, 2020), üç farklı sedimentasyon aşamasını göstermektedir: orta düzeyde (1981-1989), hızlanma (1989-1998) ve kritik (1998-2018).

More comprehensive watershed management, such as terracing on slopes greater than 15°, reforestation of high-erosion areas, strategic placement of check dams, and the implementation of improved agricultural practices, could reduce sediment by 80%, potentially extending dam operational lifespan beyond 100 years. These forecasts show that immediate conservation action is required to ensure dam viability and long-term water security in the Mellegue watershed.

The rainfall-sediment export relationship (Figure 2) verifies our modeling approach and offers critical information about watershed management timing. The lag effect between drought and peak erosion recommends that conservation efforts should be concentrated during drought periods rather than after harm has occurred. This study has obvious implications for Mellegue2 Dam management, since proactive plant establishment and soil preservation during dry years may prevent the exponential sediment loading seen during the following recovery periods.

Priority management measures are proposed for three separate zones based on geographic analysis of erosion patterns and sediment connection. High-priority sites (>12 t/ha/year) located on northwestern slopes require immediate terracing on slopes greater than 20°, intensive reforestation with native Mediterranean species, and the installation of sediment retention devices, with a projected sediment reduction of 70-80%. Moderate-priority zones (3-12 t/ha/year) in the central watershed require contour farming, agroforestry system integration, and grass waterways in drainage channels to achieve a 40-60% sediment reduction. Low-risk locations (<3 t/ha/year) require maintaining present vegetation cover, implementing rotational grazing, and monitoring erosion programs. Our strategy is to tackle the biggest threats head-on. We will begin by focusing our resources on the highest-risk zones during the first three years. This is not a one-time fix, though; we will follow that up with work in moderate-risk areas from years three to seven. To keep everything in good shape, we will have an ongoing maintenance program that kicks in during year five and continues for years to come. By prioritizing our efforts this way, we can be sure we are getting the most out of our resources and ensuring the long-term stability of the dam and the watershed.

The broader Mediterranean context of our findings highlights the Mellegue2 study's regional significance. Comparative investigation of similar semi-arid watersheds in Spain, Italy, and Greece finds consistent trends in climate-driven erosion processes, supporting our modeling approach and management recommendations. The drought-flush mechanism discovered in our study is a basic Mediterranean erosion process that necessitates coordinated regional control techniques. Our quantitative projections of dam lifespan extension through focused interventions are consistent with successful Mediterranean basin conservation initiatives, implying that the Mellegue2 strategy might be used as a model for similar watersheds dealing with climate-driven sedimentation issues.

CONCLUSIONS

The Mellegue2 Dam watershed was modeled using the combined RUSLE-IC-SDR technique, which shows erosion hazards and modeled management scenarios while offering valuable insights into sediment dynamics. With yearly forecast uncertainties ranging from -18% to +22%, the model demonstrated satisfactory performance (NSE=0.78, R^2=0.82), calling for adaptive management strategies in dynamic environments.

Key findings show that post-drought sediment outputs rise by 40–60% as a result of decreased plant cover and enhanced rainfall episodes, revealing a “drought-flush” erosion mechanism typical of Mediterranean climates. Three areas were identified by spatial analysis as management priority zones, with northwestern slopes (>12 t/ha/year) needing urgent attention.

The modeling results suggest that without conservation measures, Mellegue2 Dam may lose half of its capacity in approximately 24 years based on observed sedimentation patterns. However, the scenario analysis indicates that targeted conservation approaches like terracing, reforestation, and check dams could significantly extend the dam's operational life, with comprehensive management models showing possible extensions of 50-75 years under present climate conditions.

This study has several limitations, including difficulties in capturing extreme weather events and detailed sediment transport processes, which point to opportunities for future research using more detailed data and advanced process-based models. Ongoing field validation and long-term monitoring will be crucial for improving predictions and adjusting methods to changing climate patterns.

The research tackles important water security challenges in Tunisia and presents a modeling approach that could be relevant to similar Mediterranean semi-arid watersheds with comparable environmental conditions. The results suggest that proactive, science-based management strategies may help protect dam infrastructure and maintain watershed stability, although their long-term success will depend on continuous monitoring and flexible management practices.

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Araştırma Makalesi / *Research Article*

Mineral Reaction Kinetics During CO_2 Sequestration into Paleozoic Metamorphic Rocks

Paleozoyik Yaşlı Metamorfik Kayaçlara CO_2 Tutulumu Sırasında Mineral Tepkime Kinetiği

Hakki AYDIN[1*], Selçuk EROL[2], Serhat AKIN[3]
[1] *Zorlu Energy Group, Sarayköy, Denizli, Türkiye*
[2] *Izmir Institute of Technology, Izmir, Türkiye*
[3] *Middle East Technical University, Ankara, Türkiye*

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ABSTRACT

Carbon dioxide (CO_2) sequestration into geological formations is one of the most reliable methods for mitigating CO_2 emissions. Geothermal reservoirs are excellent candidates for CO_2 trapping due to considerable fracture pore volume, which provides safe and permanent storage. The stability of the target reservoir rock and caprock is a critical topic during long-term CO_2 sequestration. This study examines the geochemical changes resulting from reactions between geothermal reservoir rock and CO_2-saturated brine. The ultimate aim is to understand the efficiency of CO_2 sequestration in a metamorphic geothermal reservoir regarding its geochemical impact. The study involves batch experiments on core samples taken from depths of 1900 m and 3000 m in the Kızıldere geothermal reservoir in western Türkiye. We exposed crushed core samples to CO_2-saturated geothermal brine at a temperature of 95 °C and a pressure of 10 bar for 21 days. Experimental changes in the concentrations of major elements (Mg^{2+}, Ca^{2+}, Al^{3+}, Fe^{2+}, SiO_2, and Cl^-) were simulated using PHREEQC software. Kinetic rates and activation energy were utilized as tuning parameters to align simulation outcomes with experimental observations. The behavior of Mg^{2+} and Ca^{2+} exhibited an increasing trend, while SiO_2, Al^{3+}, and Fe^{2+} demonstrated a decreasing trend. Consequently, the interaction between CO_2-saturated brine and reservoir rock resulted in the precipitation of K-feldspar and kaolinite minerals, whereas other minerals, such as biotite, quartz, magnesite, and siderite, exhibited slight dissolution. The mineral assemblage remained consistent, while the abundance of the minerals exhibited slight variations. The study indicates that a high concentration of cations may facilitate the trapping of CO_2 within metamorphic rocks. Furthermore, solubility trapping was determined to be more significant than mineral trapping in the batch experiments.

Keywords: Carbon dioxide sequestration, mineral alteration, geothermal energy

ÖZ

Jeolojik formasyonlara karbondioksit (CO_2) tutulumu, CO_2 emisyonlarını azaltmak için en güvenilir yöntemlerden biridir. Jeotermal rezervuarlar, geniş kırık-gözenek hacimleri sayesinde CO_2 tutumu için güvenli ve kalıcı depolama fırsatları sunan mükemmel adaylardır. Hedef rezervuar kayacı ve örtü kayacın uzun dönem CO_2 enjeksiyonu süresince kararlılığı ise kritik bir konudur. Bu çalışma, jeotermal rezervuar kayacı ile CO_2 doygunluğundaki akışkan arasındaki reaksiyonlar sonucu oluşan jeokimyasal değişimleri incelemektedir. Nihai amaç, metamorfik bir jeotermal rezervuarda CO_2 tutumunun jeokimyasal etkiler açısından etkinliğini ortaya koymaktır. Çalışma

Sorumlu yazar / *Corresponding author:* hakki_aydin1990@hotmail.com

kapsamında, Türkiye'nin Batısında yer alan Kızıldere jeotermal rezervuarında 1900 m ve 3000 m derinliklerden alınan karot numuneleriyle kesikli (batch) deneyler gerçekleştirilmiştir. Ufaltılmış karot örnekleri, 95 °C sıcaklık ve 10 bar basınçta CO_2 doygunluğundaki jeotermal akışkana 21 gün süreyle maruz bırakılmıştır. Mg^{2+}, Ca^{2+}, Al^{3+}, Fe^{2+}, SiO_2 ve Cl^- gibi temel element konsantrasyonlarındaki deneysel değişimler PHREEQC yazılımı kullanılarak modellenmiştir. Simülasyon çıktılarının deneysel gözlemlerle uyumlu olması için kinetik hızlar ve aktivasyon enerjisi ayar parametreleri olarak kullanılmıştır. Mg^{2+} ve Ca^{2+} konsantrasyonları artış eğilimi gösterirken; SiO_2, Al^{3+} ve Fe^{2+} azalma eğilimi göstermiştir. Bu durum, CO_2 doygun akışkan ile rezervuar kayacı arasındaki etkileşim sonucunda K-feldispat ve kaolinit minerallerinin çökelmesine yol açmış; biyotit, kuvars, manyezit ve siderit gibi diğer minerallerde ise hafif çözünme meydana gelmiştir. Mineral topluluğu genel olarak sabit kalmış, ancak minerallerin bollukları küçük değişiklikler göstermiştir. Çalışma, yüksek katyon konsantrasyonlarının metamorfik kayaçlar içerisinde CO_2 tutumunu kolaylaştırabileceğini ortaya koymuştur. Ayrıca, gerçekleştirilen kesikli deneylerinde çözelti fazında CO_2 tutulumunun mineral tutulumuna kıyasla daha baskın olduğu belirlenmiştir.

Anahtar Kelimeler: *Karbondioksit tutulumu, mineral alterasyonu, jeotermal enerji*

INTRODUCTION

The terms "global warming" and "climate change" denote long-term alterations in atmospheric conditions, including humidity, temperature, and precipitation patterns, attributed to elevated anthropogenic CO_2 levels and other greenhouse gas emissions (Thuiller, 2007; Taylor et al. 2013). Researchers are actively exploring strategies to diminish CO_2 emissions and manage climate change effectively. The sequestration of CO_2 into geological formations represents one of the most dependable and secure techniques for alleviating gas emissions that contribute to global warming (Bachu, 2000; Shukla et al., 2010; Andre et al., 2012; Jin et al., 2016). Deep geothermal reservoirs are recognized as promising geological formations for the long-term sequestration of carbon dioxide (CO_2). Capturing the CO_2 emissions from geothermal sites and reinjecting them into the original geothermal reservoir constitutes an additional method to mitigate emissions. In the CarbFix method (Aradottir et al., 2012), the geothermal effluent is combined with the captured non-condensable gas (NCG) and cold pond water. The resulting CO_2-saturated brine is then injected into the same geothermal reservoir (Clark et al., 2020; Galeczka et al., 2022). Throughout this process, the injected CO_2 is first captured via solubility trapping. This CO_2 can subsequently convert into bicarbonate and carbonic acid when it interacts with the formation brine. This interaction triggers complex chemical reactions that allow CO_2 to be sequestered in a secondary mineral phase as carbonate, depending on the prevailing thermodynamic conditions and the presence of primary mineral phases (Matter et al., 2016; Přikryl et al., 2018). Primary minerals crystallize directly from magma and are mainly found in igneous rocks, while secondary minerals form through the alteration or weathering of primary minerals (Berndsen et al., 2024). Following the success of the CarbFix projects, the insights gained are being applied to other geothermal sites across Europe, such as those in Türkiye and Italy, under the Geothermal Emission Control H2020 project (GECO, 2020; GECO, 2023).

Geological CO_2 storage capacity depends on the volume, as well as the chemical and mineralogical composition of the formation brine and reservoir rock, respectively. CO_2 sequestration can be achieved through the following mechanisms:

- CO_2 dissolution in formation water, which is called solubility trapping
- Mineral trapping as a result of interactions between CO_2-saturated water and the rock
- CO_2 accumulation at the top of geological strata called structural trapping
- Hydrodynamic trapping occurs when the density of CO_2 is near that of the formation brine (Zhang & Song, 2019)
- Capillary trapping involves CO_2 injection into a saline aquifer (drainage process), and brine is passively re-imbibed into the pore space (imbibition process) (Teng et al., 2022)

Long-term structural trapping, capillary trapping, and hydrodynamic trapping may pose risks, including gas leakage through conductive faults, cementing failure, and surface deformation. Therefore, mineral and solubility trapping are considered the most reliable and safe mechanisms to mitigate CO_2 emissions. Geothermal reservoirs are suitable candidates for this purpose due to their large brine volume. However, it is important to note that CO_2 solubility decreases with increasing salinity (Duan and Suni, 2003; Duan et al., 2006). To minimize risks before field-scale CO_2 injections, experimental and simulation-based studies are typically conducted to delineate possible effects on well integrity, reservoir rock, and caprock.

Interactions between brine and rock can be analyzed through the implementation of batch and core-flood experiments. Reactive minerals, as well as both primary and secondary minerals, can be acquired through laboratory tests. However, it is important to note that laboratory experiments may be insufficient to fully account for the intricate reaction pathways present in natural systems (Hellevang et al., 2013). Furthermore, numerical simulations are capable of forecasting reactive-transport processes in complex natural systems over extensive timeframes, potentially spanning thousands of years. These numerical simulations necessitate the availability of thermodynamic and kinetic data to ensure the accuracy of these predictions. Barlas et al. (2024) simulated CO_2 injection into the Kızıldere geothermal field and reported that the results of the CO_2-charged brine injection showed that approximately 20% of the injected CO_2 circulated in the reservoir, ensuring reduced CO_2 emissions. Hydrothermal alteration constitutes a complex process characterized by a range of chemical, textural, and mineralogical transformations that indicate fluid circulation within geothermal formations. This process occurs during the stages of recharge, upward flow, and burial metamorphism. Types of alteration may vary based on critical parameters such as deposit type, environmental temperature, pressure, fluid-to-rock ratio, and fluid content. The extent of the alteration zone may range from a few centimeters to several kilometers. There are two primary divisions of alteration: hypogene alteration and supergene alteration. An increase in temperature typically induces hypogene alteration, whereas supergene alteration occurs because of meteoric water reactions in low-temperature environments (Brimhall and Ghiorso, 1983). Notable mineral alterations include potassic alteration, phyllic alteration, propylitic alteration, argillic alteration, silicification, carbonization, greisenization, and hematitization (Wallace & Maher, 2019; Seki, 1973; Parry et al., 2002; Di Tommaso & Rubinstein, 2007). Potassic alteration occurs by replacing plagioclase and mafic silicates at temperatures between 450 and 600 °C. K-silicate is characterized by K-feldspar, biotite, minor quartz, and chlorite (Battles and Barton, 1995). Propylitic alteration occurs through the addition of H_2O, CO_2, and local S, without appreciable H^+

metamorphism. Chlorite and epidote primarily exist alongside lesser amounts of calcite, albite, and zoisite in a propylitic alteration environment (Binglin et al., 2014). Propylitic alteration is found at low to intermediate temperatures (200-350 °C) and low fluid-rock ratios. The destabilization of feldspars results in sericitic alteration through hydrolysis in the presence of K, S, and OH, forming quartz, chlorite, pyrite, and sericite (Meunier & Velde, 1976). This process involves leaching out of Mg, Fe, Na, Ti, and K. Argillic alteration is categorized into intermediate and advanced argillic depending on the intensity of the clay mineral. Intermediate argillic alteration is characterized by the formation of smectite and kaolinite groups at temperatures below 250 °C (Hikov, 2004). Silicification involves forming new quartz or amorphous silica minerals as a result of isochemical hydrolysis reactions in the local presence of Si. Quartz precipitation occurs in fractures where hydrothermal fluids flow. High-level epithermal precious metal ore deposits influence silicification (Kumar & Ghassemi, 2005). Carbonatization refers to the formation of carbonate minerals such as dolomite, calcite, siderite, and magnesite during rock alteration. Mineral carbonation requires metallic cations such as Mg^{2+}, Ca^{2+}, and Fe^{2+}. Greisenization represents the alteration of muscovite, quartz, and lesser fluorite (Witt, 1988). It is a post-magmatic alteration that changes the composition of granites through several sequential stages. It is a metasomatic process related to high silica leucocratic granitoid (Stemprok, 1987). A summary of alteration types and their mineral compositions is shown in Table 1. Secondary minerals observed in western Türkiye are presented in Table 2.

Table 1. Diagnostic minerals in hydrothermally-altered volcanogenic massive sulfide deposits at various metamorphic grades (Alt et al., 2012).

Çizelge 1. Farklı metamorfizma derecelerine uğramış hidrotermal olarak altere olmuş volkanik kökenli masif sülfit yataklarındaki tanısal mineraller (Alt vd., 2012).

Alteration type	**Diagnostic minerals: unmetamorphosed deposits**	**Diagnostic minerals: greenschist facies**	**Diagnostic minerals: granulite facies**
Advanced argillic	Kaolinite, alunite, opal, smectite	Kaolinite, pyrophyllite, andalusite, corundum, topaz	Sillimanite, kyanite, quartz
Argillic	Sericite, illite, smectite, pyrophyllite, opal	Sericite, illite, pyrophyllite	Sillimanite, kyanite, quartz, biotite, cordierite, garnet
Sericitic	Sericite, illite, pyrophyllite	Sericite, illite, quartz	Biotite, K-feldspar, sillimanite, kyanite, quartz, cordierite, garnet
Chloritic	Chlorite, quartz, sericite	Chlorite, quartz, sericite	Cordierite, orthopyroxene, orthoamphibole, phlogopite, sillimanite, kyanite
Carbonate propylitic	Carbonate (Fe, Mg), epidote, chlorite, sericite, feldspar	Carbonate (Fe, Mg), epidote, chlorite, sericite, feldspar	Carbonate, garnet, epidote, hornblende, diopside, orthopyroxene

Table 2. Secondary minerals observed as a result of water-rock interaction in western Türkiye.
Çizelge 2. Batı Türkiye'de su–kayaç etkileşimleriyle oluşan ikincil mineral toplulukları.

Field ID	**Water type**	**Reservoir rock type**	**Hydrothermal Alteration**	**References**
Aydın-Salavatlı Geothermal Field	Na-HCO_3	Menderes metamorphic reservoir rock (calc-schist, mica-schist, quartzite, gneiss, marble)	Kaolinite, illite, montmorillonite, calcite, pyrite, dolomite, and hydro biotite	Karamanderesi & Helvaci, 2003
Alaşehir Geothermal Field	Na-HCO_3	Menderes metamorphic reservoir rock (calc-schist, mica-schist, quartzite, marble)	Chloritization, sericitization, silicification, carbonification	İlhan & Kabak, 2018
Kızıldere Geothermal Field	Na-HCO_3SO_4	Menderes metamorphic reservoir rock (calc-schist, mica-schist, quartzite, marble)	Phyllic, argillic, silicic, hematized, and carbonatized alteration zones	Özgür, 2010

Geological storage of carbon dioxide is a slow process that may require years. Critical parameters influencing the reaction time include mineral surface area, mineral types, thermodynamic conditions, and CO_2 saturation. Flow-through experiments can take months to years to understand brine-rock interaction due to the limited contact surface area. In contrast, batch experiments have a considerably shorter experimental time due to the high mineral surface area of rock in powder form. Consequently, laboratory test results typically provide some insights into process initiation. In this regard, reactive transport simulations calibrated with experimental results are generally employed to understand the effects of CO_2 reinjection on the reservoir rock and fluid (Ratouis et al., 2021; Ratouis et al., 2022; Erol et al., 2022a). Kinetic reaction rates and mineral surface area significantly influence fluid-rock interaction. Estimating reservoir mineral surface area can be challenging in heterogeneous systems. Therefore, sensitivity analyses are performed to understand its impact on the results. Reaction rates obtained from laboratory tests may differ from those determined in natural field settings (White & Brantley, 2003). Kampman et al. (2014) noted that direct sampling of CO_2-rich fluids is complicated due to CO_2 degassing during sampling. Waldmann et al. (2014) investigated the significance of mineral surface area on CO_2-brine-rock interactions. They studied the effects of specific mineral surface areas, mineral distribution, and whole rock surface areas separately. The study demonstrated that the initial amounts of K-feldspar, hematite, kaolinite, and carbonate control clay mineral precipitation during CO_2 storage in Rotliegend sandstones.

Gaseous impurities can lead to various reactions at different kinetic rates. Pearce et al. (2015) conducted both experimental and simulation studies to investigate the impact of SO_2 on CO_2-brine-rock interactions. The dissolution of SO_2 in water produced sulfuric acid, which intensified the dissolution of silicates and carbonates. The degree of mineral dissolution varies depending on the rock composition. Their research indicated that high cation concentrations may enhance CO_2 trapping. Wang et al. (2016) investigated CO_2-brine-rock interactions for CO_2 sequestration in deep coal seams through experimental methods. Their experiments utilized powdered rock samples to simulate caprock in a batch system, conducted at 160 °C and 15 MPa. They analyzed changes in mineralogical composition using X-ray diffraction (XRD) and energy dispersive X-ray spectroscopy with scanning electron microscopy (EDX-SEM) techniques.

Batch reactor experiments effectively enhance our understanding of the interactions between CO_2-saturated brine and reservoir rock under actual reservoir conditions. Steel et al. (2018) carried out hydrothermal experiments lasting over six months to investigate the potential for mineral carbonation through brine buffering with calcite. These experiments were subsequently simulated using PHREEQC to assess the equilibrium state. The findings indicated that the buffering effect of calcite was inadequate to promote mineral carbonation. Liu et al. (2012) examined reactive experiments involving CO_2, brine, and caprock, presenting the Eau Claire formation as a case study. A batch experiment was executed at 200 °C and 300 bars. Stable isotope tests indicated the presence of CO_2 in both free and dissolved phases within the caprock. The study noted the precipitation of clay and carbonate minerals alongside the dissolution of feldspars and carbonate minerals. Liu et al. (2018) explored CO_2-brine-rock interactions aimed at CO_2 sequestration in a deep saline aquifer. They conducted experiments using minerals sourced from the upper layer of the Shahejie formation in China. The results revealed significant changes in ion concentrations after 72 hours of reaction time, with notable increases in HCO_3 and Ca^{2+} concentrations.

Water-rock interaction experiments and simulations are critical components of CO_2 sequestration projects. This study investigates CO_2 sequestration in Paleozoic geothermal reservoir rocks. The results of batch experiments, coupled with a modeling approach, are used to understand water-rock interaction during injection of brine containing dissolved CO_2. Geochemical changes in the brine and mineral alterations were measured through analyses of both water and rock. Important parameters, such as mineral surface area, kinetic reaction rate, and activation energy, affecting water-rock interaction were determined by matching experimental results with a modeling approach using PHREEQC.

GEOLOGY OF KIZILDERE GEOTHERMAL SYSTEM

The Kızıldere geothermal field is located at the eastern boundary of the Büyük Menderes graben, one of the most active extensional structures within the western Anatolian graben-horst system. The Kızıldere field developed within an extensional domain play type, where convective and conductive heat flow effectively dominate geothermal activity. Various tectonic movements have influenced Western Anatolia over time. These have led to crustal thinning and the formation of large grabens in the region (Şengör & Yılmaz, 1981).

The stratigraphy of this field comprises Paleozoic metamorphic units of the Menderes Massif, overlain by Pliocene and Quaternary sedimentary rocks. The rock units cropping out near the Kızıldere geothermal field were studied by various researchers (Şimşek, 1984; Sun, 1990; Bozkurt, 2000; Kaymakçı, 2006; Alçiçek et al., 2007; Gürer et al., 2009; Koçyiğit, 2015). There is no consensus about the names and ages of the units in the region, as shown in Figure 1. However, a recent study by Aksu (2019) is based on a definition of formations derived from drilling more than 100 geothermal wells and is more widely used in field operations. The stratigraphy of the study area, from oldest to youngest, comprises the Menderes Massif, the Kızılburun Formation, the Sazak Formation, the Kolankaya Formation, the Tosunlar Formation, and Quaternary alluvial deposits.

The Menderes Massif, first identified and named by Philipson (1918), is the largest tectonic unit in western Anatolia. Bozkurt and Oberhansli (2001) classified the Menderes Massif into two rock groups: core rocks and cover rocks. Core rocks include augen gneiss, metagranite, quartzite, and other high-pressure, high-temperature metamorphic rocks (Şengör et al., 1984). Aksu (2019) described augen gneiss as very coarse-grained, brittle, extensively weathered, and highly fractured in the Kızıldere field outcrops. The cover rocks include low-grade quartzite, schist, and marble. Schist bands in the region include calc-schist, quartz-muscovite-schist, mica-schist, and chlorite-schist. The age of the cover rocks is Mesozoic-Paleozoic (Boray, 1982).

The Kızılburun Formation dates back to the Early Miocene to Early Middle Miocene period (Alçiçek et al., 2007). It overlies the Menderes Massif and can be described as matrix-supported, unsorted, polygenetic boulder-block conglomerates with intercalations of red-brown mudstone and sandstone (Aksu, 2019).

The Sazak Formation conformably overlies the Kızılburun Formation. Its lower section features gray-green marl, brown claystone, and alternating layers of clayey limestone. The middle section is marked by massive limestone beds alternating with sandstones. The upper section comprises clayey limestone and organic-rich calcareous shale facies. The karstic characteristics and brittle rheology of the Sazak Formation make it a highly effective reservoir for the geothermal system in the Kızıldere field. Hot springs and fumeroles are observed in the limestone units of the Sazak Formation in the study area.

The Kolankaya Formation is characterized by laminated marl with occasional intercalations of sandstone and bioclastic limestone. Marl deposits suggest a much deeper, low-energy lacustrine environment with brackish water conditions compared to the Sazak Formation (Alçiçek et al., 2007).

The Tosunlar Formation lies above all older rocks, separated by a regional unconformity. It is composed of yellow-brown, polygenetic, poorly-sorted conglomerates made of pebbles and boulders, with occasional mudstone layers. The formation was deposited as a fault-controlled high-energy debris flow along mountain fronts (Aksu, 2019).

Holocene units comprise loose, poorly-sorted materials including pebbles, sands, and muds from alluvial fan and fluvial deposits. Alluvial fan deposits are located near the basin margins, whereas fluvial alluvium deposits are found in the basin center.

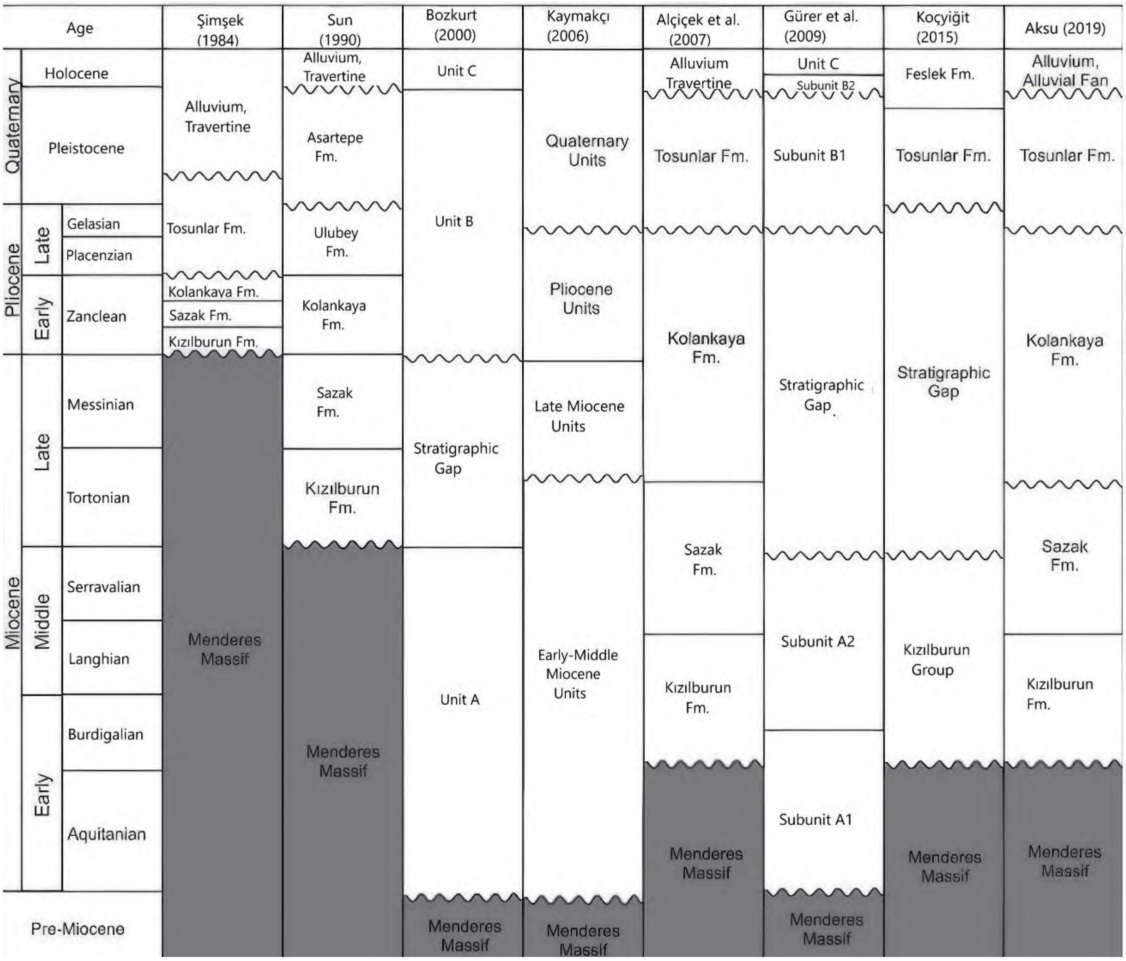

Figure 1. Stratigraphic comparison from previous studies based near Kızıldere geothermal field (adapted from Aksu, 2019).

Şekil 1. Kızıldere jeotermal sahası çevresinde derlenen önceki çalışmaların stratigrafik karşılaştırması (Aksu, 2019'dan revize edilmiştir).

In the Kızıldere geothermal field, there are four main productive reservoir sections arranged by increasing depth: Sazak Formation (Reservoir I), İgdecik Formation (Reservoir II), fractured quartzite-calcschist of the Menderes Metamorphics (Reservoir III), and the deep marble section of the Menderes Metamorphics (Reservoir IV) (Haklıdır et al., 2021). The sections where core samples were collected during the drilling of a geothermal well are shown in Figure 2.

Core sample #1 was retrieved from a depth of 1900 meters, where the reservoir rock is characterized as quartzite with white, dirty white, greenish, dull, transparent, and translucent features. It is extremely hard, with microfractures, containing mica flakes, trace pyrite, infilling silica, and chlorite schist banding. Core sample

#2 was collected from a depth of 3000 m, where the reservoir rock is marble characterized by light to dark grey coloration, mottled, hard to extremely hard, microcrystalline, fractured and microfractured, partly silicified, massive, tight texture, and intercalated with calcschist. It is essential to note that the mineralogical composition of the core samples does not represent the entire reservoir rock, but rather a single point within the highly heterogeneous system.

A geological map of the study area at a scale of 1:25000 is presented in Figure 3. Outcrops of geological units can be observed in the field. Three fault types were identified in the geothermal system: approximately E-W-striking high-angle normal faults, N-S-striking subvertical faults, and an old low-angle detachment fault that likely developed prior to the other faults. Geothermal wells that target intersecting faults at reservoir depths deliver good production results because fractures enhance secondary permeability.

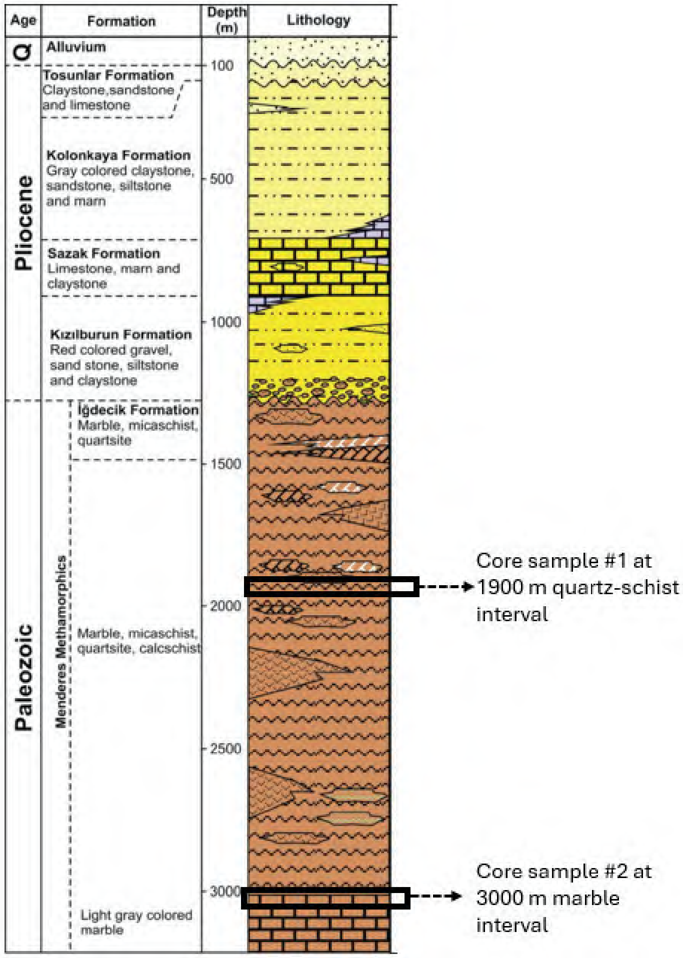

Figure 2. Geological columnar section and depths of core samples from the study area (adapted from Haklıdır et al., 2021)

Şekil 2. Jeolojik sütun kesiti ve karot örneklerinin derinlikleri (Haklıdır vd., 2021'den revize edilmiştir).

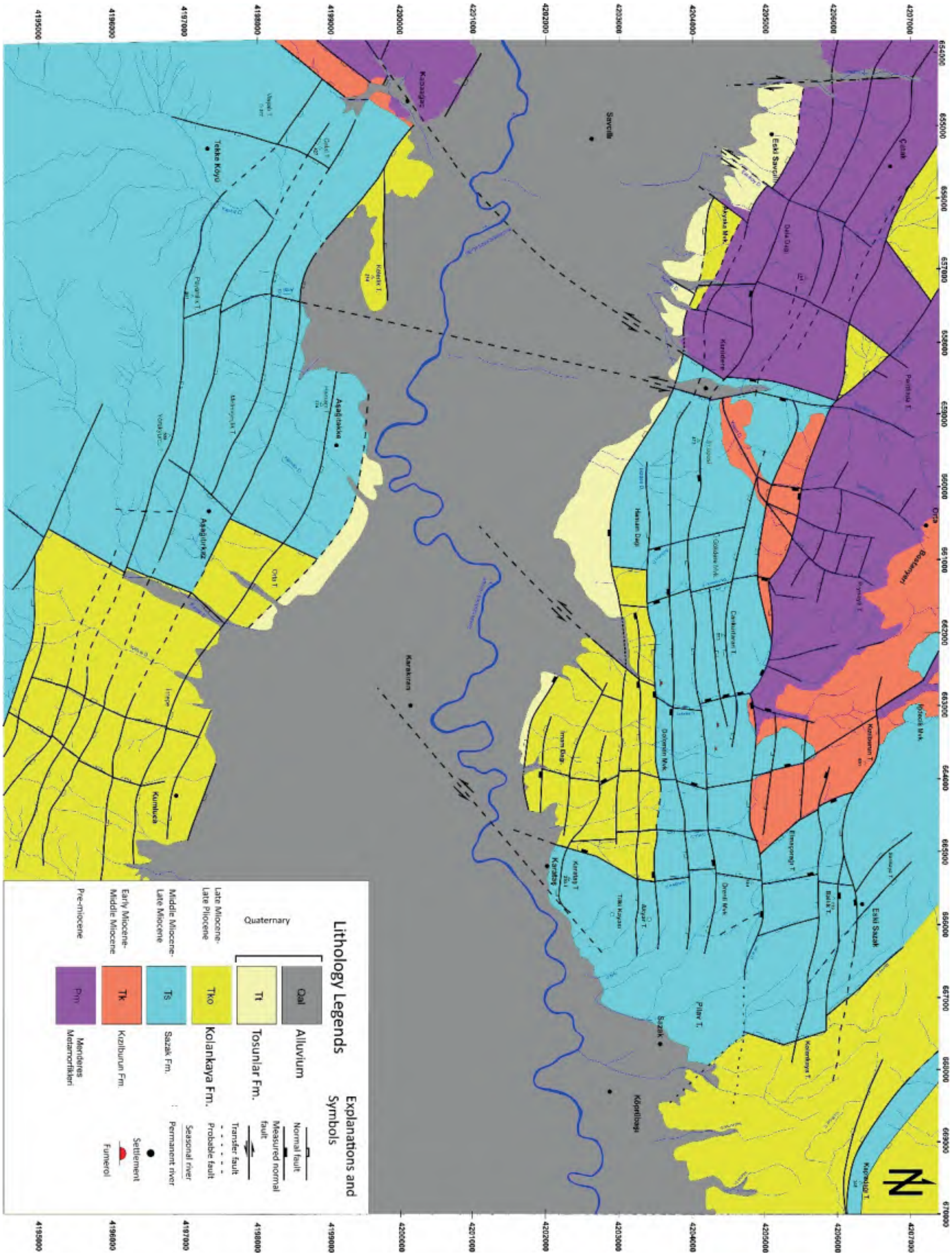

Figure 3. Geological map of the study area (after Aksu, 2019).

Şekil 3. Çalışma alanının jeolojik haritası (Aksu, 2019'dan alınmıştır).

MATERIALS AND METHODS

The workflow for the study is depicted in Figure 4. The study started by collecting actual geothermal brine and NCG (more than 99% CO_2) from geothermal wells. Core samples were taken from depths of 1900 m and 3000 m in the Kızıldere geothermal reservoir in Türkiye (Senturk et al., 2020). The core samples were then crushed and screened into particle sizes. The methodology and the experimental setup process are presented in Aydin and Akin (2023). Each batch experiment was performed twice under the same conditions to ensure consistency and evaluate reproducibility. The results are the averages of these repeated runs. Any variation between duplicates remained within acceptable analytical uncertainty. Rock analysis was performed before and after batch experiments using XRD, EDX-SEM, and a polarized light microscope. XRD analyses of the powdered samples were performed at Pamukkale University Advanced Technology Research and Application Center (PAU-ILTAM) Laboratory using a GNR APD 2000 diffractometer. The instrument features a Cu-Kα cathode tube (wavelength: 1.54 Å) and operates under the following conditions: voltage of 10–60 kV, current of 5–60 mA, scanning speed of 0.1°(2θ/s), and scanning range from 111° to 168° (2θ). Based on the resulting XRD patterns, mineralogical identifications and the relative abundances of minerals (%) were determined. SEM-EDS analyses were conducted at the Advanced Research Techniques Laboratory of Pamukkale University using a Carl Zeiss FESEM Supra 40 VP field emission scanning electron microscope. Backscattered electron (BSE) imaging was used to obtain microstructural data, and semi-quantitative chemical compositions of minerals in the core samples were determined with a Quantax Bruker EDS system. Polarized light microscope measurements were carried out at the Department of Geological Engineering, Pamukkale University, using a Carl Zeiss Primotech polarizing microscope equipped with both transmitted and reflected light illumination.

Additionally, image processing was employed to determine the mineral surface area, a critical parameter for modeling the reaction process. Similarly, geochemical measurements of major elements were conducted before and after the batch experiments. In batch experiments, the PHREEQC code was used to simulate water-rock interaction between CO_2-saturated geothermal brine and rock particles (Parkhurst & Appelo, 2013). The tuning parameters were the activation energy and the kinetic reaction rates of minerals, which were adjusted to match the simulation data with the concentrations of elements obtained from experiments.

The study features batch experiments focused on the interaction between rock powders and CO_2-saturated geothermal brine. An illustration of the experimental setup is depicted in Figure 5. This arrangement includes a reactor with a 12-liter inner volume, geothermal heating, a mixer (shown in Figure 6d), a Sierra-branded gas flow meter (Figure 6a), a high-pressure gas source tube, a two-stage regulator, sampling ports, and a mini separator (Figure 6a). To minimize reactions that could alter the geothermal brine, stainless steel components were employed. Two ¼-inch injection ports (Figure 6b) are positioned at the reactor's top to facilitate the injection of gas and brine. A pressure relief valve ensures safe pressure release in the event of uncontrolled increases within the reactor. The batch reactor includes a mixer with a power rating of 0.75 kW (Figure 6c), a 300-rpm reducer, Teflon packing, and a specialized sealing system, allowing continuous mixing at elevated temperatures and pressures. The system's temperature and pressure are constantly recorded by a thermocouple and a pressure transmitter located at the bottom of the reactor. Insulation materials and a double-stage gas regulator maintain stable temperature and pressure conditions during experiments. The reactor is heated using the temperature of the geothermal brine from the production line. Brine samples are taken from the sampling port at the bottom of the reactor and routed to a mini separator under atmospheric conditions. Here, the flashed brine sample separates into gas and liquid phases, with brine samples collected from the bottom port of the mini separator. The gas phase is funneled into a steam condenser to remove steam from NCG, while pure and dry CO_2 is quantified using a gas flow meter.

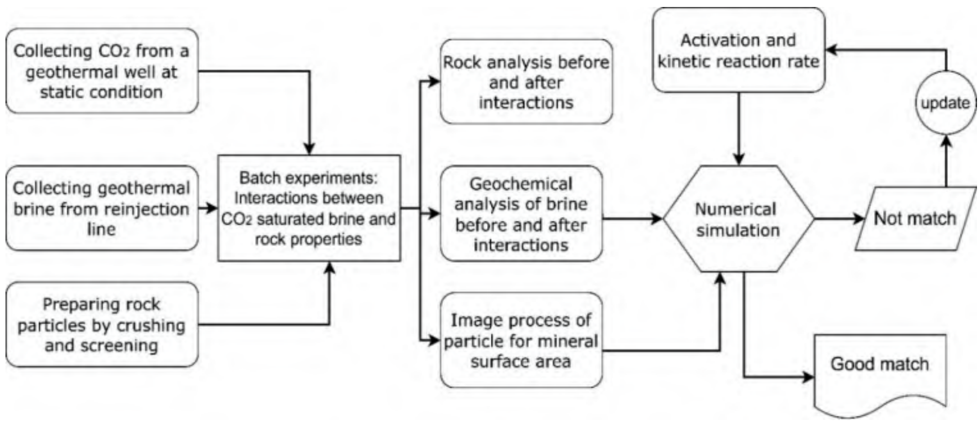

Figure 4. Workflow of the study.
Şekil 4. Çalışmanın iş akışı.

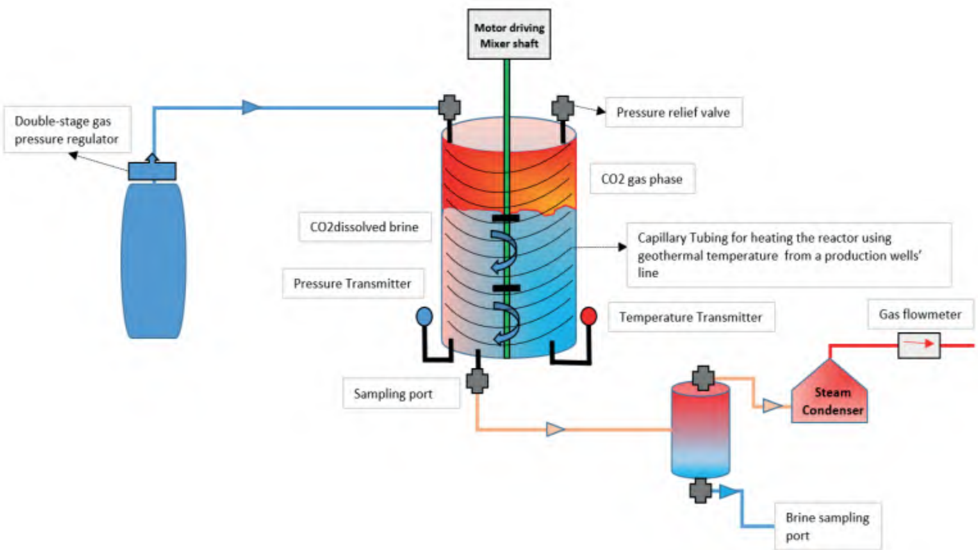

Figure 5. Illustration of the experimental setup.
Şekil 5. Deney düzeneğinin şematik gösterimi.

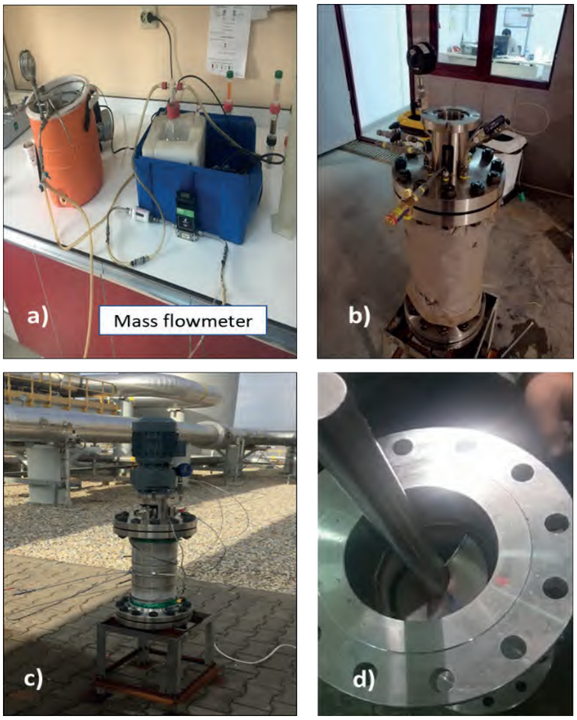

Figure 6. Equipment in the experimental setup; a) mass flowmeter and condenser, b) relief valve, gas and liquid injecting ports, c) reactor with a mixing motor and heating system, and d) mixer and rotor

Şekil 6. Deney düzeneğinde kullanılan ekipmanlar: a) Kütlesel debimetre ve yoğuşturucu.

b) Emniyet vanası, gaz ve sıvı enjeksiyon girişleri c) Karıştırma motoru ve ısıtma sistemi bulunan reactor d) Karıştırıcı ve rotor.

The geothermal brine (9 liters) was gathered from an injection well in the Alaşehir field and introduced into the reactor. CO_2 was likewise sourced from a geothermal well, maintained under static conditions with a pressure of 40 bar at the wellhead (Figure 7). The brine sample was heated using the heat from an actively-producing geothermal well and then routed into capillary tubing that is encircled by the reactor. The reactor was subsequently insulated from the atmosphere with isolating materials. Once temperature stabilization was achieved, CO_2 was supplied to the reactor at constant pressure while the system underwent continuous mixing. This consistent mixing of the fluids within the reactor maximizes the contact surface area between geothermal brine and CO_2 (Figure 8).

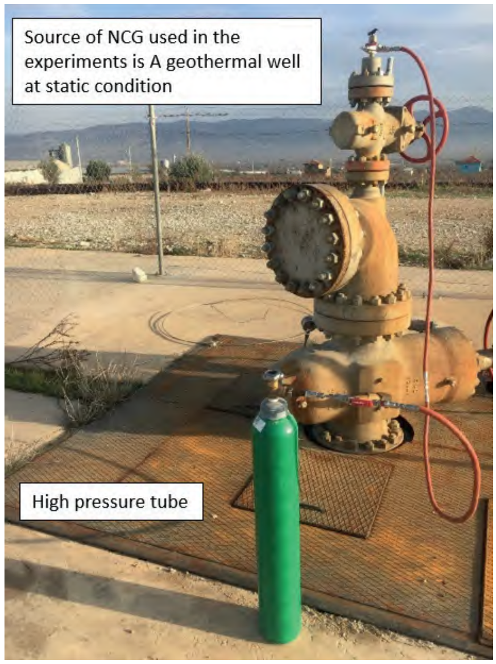

Figure 7. Gas collecting at a well for the experiments.

Şekil 7. Deneylerde kullanılan gaz toplama kuyusu.

The gas content of the NCG is shown in Table 3. As can be seen, CO_2 constitutes more than 99% of the total dry gas volume. The geothermal well has not flowed for over 16 months, and NCG accumulation occurred at the wellhead due to density differences. The geochemical content of the geothermal brine collected from the re-injection line is also presented in Table 4.

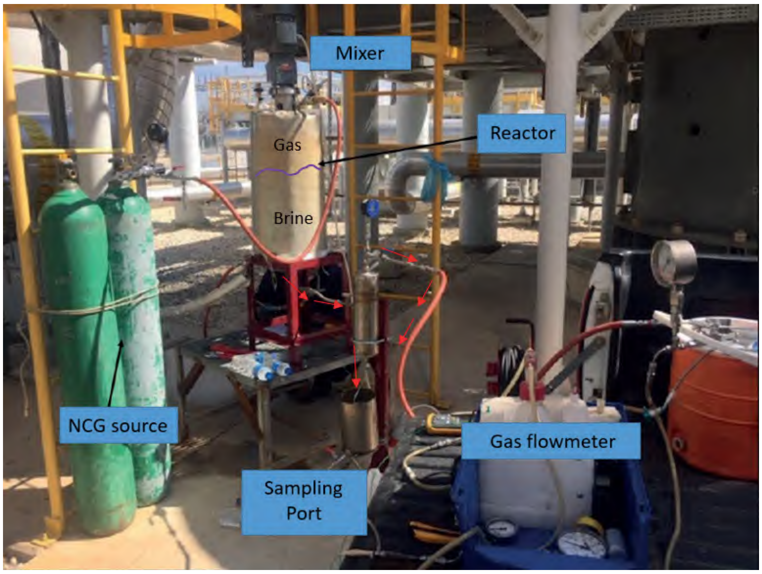

Figure 8. A view of the experimental setup in the field.

Şekil 8. Sahada kurulan deney sisteminin görünümü.

Table 3. Gas content of NCG.

Çizelge 3.Yoğuşmayan gazların (YMG) bileşimi.

Gas Composition	Volume % in dry gas
Carbon Dioxide (CO_2)	99.38
Nitrogen (N_2)	0.36
Methane (CH_4)	0.21
Hydrogen Sulfide (H_2S)	0.0036
Argon (Ar)	0.003
Hydrogen (H_2)	0.01
Helium (He)	0.00005

Table 4. Concentration of elements in geothermal brine.

Çizelge 4. Jeotermal akışkandaki element konsantrasyonları.

Element	Concentration (ppm)	Element	Concentration (ppm)
F^-	10.3	Na^+	606.6
Cl^-	306	NH_4^+	6.3
Al^{3+}	0.43	K^+	47.7
Br^-	1.35	Mg^{+2}	0.52
NO_3^-	1.06	Ca^{+2}	21
SO_4^{-2}	19.8	CO_3^{-2}	320
PO_4^{-3}	1.4	HCO_3^-	160
Li^+	4.0	Si^{+4}	120
TDS	1627		

Modeling of Batch Experiments using PHREEQC

PHREEQC version 3 (PH Redox Equilibrium), which has the capability to perform saturation index calculations and speciation, was used for aqueous geochemical calculations (Parkhurst and Appelo, 2013). PHREEQC may also be used to study mineral and gas equilibria, solution mixing, advective transport calculations, inverse modeling, surface complexation reactions, and ion exchange reactions (Parkhurst, 2005). PHREEQC can utilize different thermodynamic databases, such as the default database LLNL (Parkhurst and Appelo, 2013) or Thermoddem developed by Blanc et al. (2012). Due to the degree of crystallinity and/or the compositions of the examined mineral phases, the choice of thermodynamic dataset utilized in the calculations is a case-by-case procedure, and the various thermodynamic datasets can result in different outcomes. Akin and Kargı (2019) simulated the geochemical evolution of fluids in geothermal wells in the west of Türkiye using PHREEQC code. They used databases such as PHREEQC.dat and LLNL.dat when matching actual field measurements. The use of LLNL.dat provided a better match with the field's geochemical data. Since similar compositions of geothermal fluid have been used in this study, LLNL.dat was utilized as the reference database for the simulation of CO_2 dissolution. A code written in the PHREEQC Notepad was used for CO_2 dissolution in geothermal water and water-rock interaction. CO_2 solubility in water was solved using the Peng-Robinson equation of state (Peng & Robinson, 1976). Governing equations for water-rock interactions are presented in Equations 1 to 4. In these equations, activation energy (E) is the minimum amount of energy required for a chemical reaction to occur. Activation energy determines the rate at which mineral reactions, such as dissolution or precipitation, occur. The higher the energy activation, the slower the reaction rate at a given temperature. Kinetic reaction rates ($k_{1,2}$) describe how quickly a chemical reaction proceeds over time. For minerals, this refers to the rates at which they dissolve in a solvent or precipitate from a solution. The rate of these reactions depends on several factors, including temperature, energy activation, mineral surface area, and ionic strength.

$$k_2 = k_1 * \exp\left(\frac{E}{R} * \left(\frac{1}{T_K} - \frac{1}{298.15}\right)\right) \quad (1)$$

$$\left(\frac{A_0}{V}\right) * \left(\frac{m}{m_0}\right)^{0.67} * k_2 * (1 - SR(\text{Mineral})) \quad (2)$$

$$Moles = rate * time \quad (3)$$

$$Concentration = moles * MW * 1000 \quad (4)$$

RESULTS AND DISCUSSION

The mineral surface area A_0 was determined through image processing with ImageJ, supplemented by SEM-EDX and XRD results. XRD analyses of core samples were conducted using a GNR APD 2000PRO brand X-ray diffractometer. Core samples from depths of 1900 m and 3000 m were crushed and sorted using screeners (Figure 9).

The image processing of rock powders was conducted using ImageJ. An image of randomly mixed mineral particles was captured and introduced to ImageJ (Figure 10). By coloring the mineral particles, image processing provides volume and surface area of minerals by utilizing the roundness and size of the particles (Figure 11). The average particle area was measured as 0.398 mm² with a standard deviation of 0.167 mm². To determine the mineral surface area of each mineral type, it is necessary to obtain measurements using a polarized light microscope. (Figures 12 and 13), EDX SEM (Figures 16 and 17, Tables 5 and 6), and XRD analyses (Figures 16 and 17). The major minerals identified with EDX SEM included quartz, albite, magnesite, siderite, kaolinite, calcite, and muscovite.

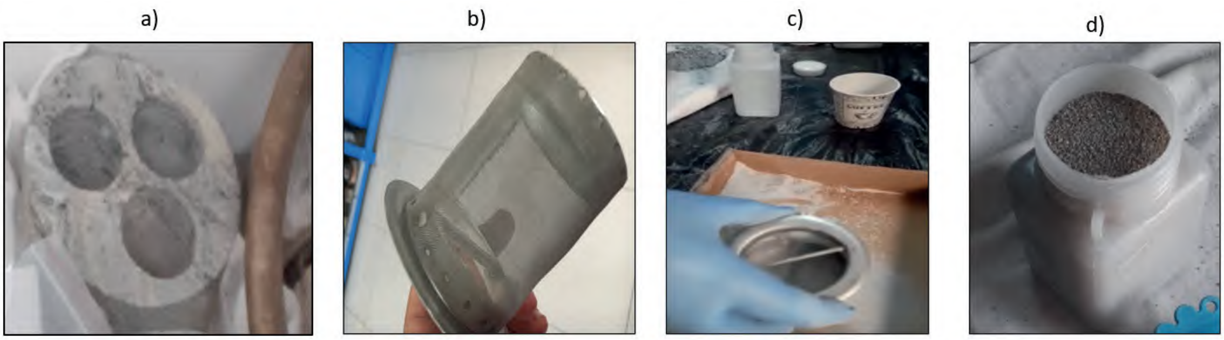

Figure 9. Crushing core samples into small particles (core sample (a) Screener (b), shaking screeners (c), separated particles (d)).

Şekil 9. Karot örneklerinin küçük partiküllere kırılması (a) karot örneği, (b) elek, (c) titreşimli elekler, (d) seçilen partiküller.

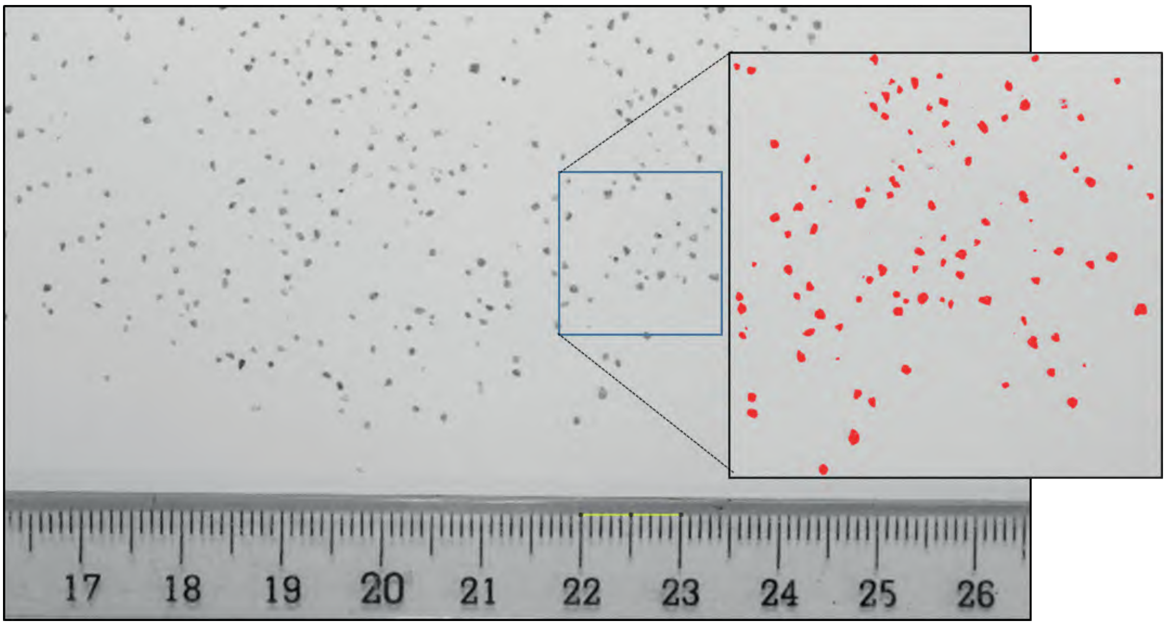

Figure 10. Image processing of rock powder using ImageJ.

Şekil 10. ImageJ ile kaya tozu partiküllerinin görüntü analizleri.

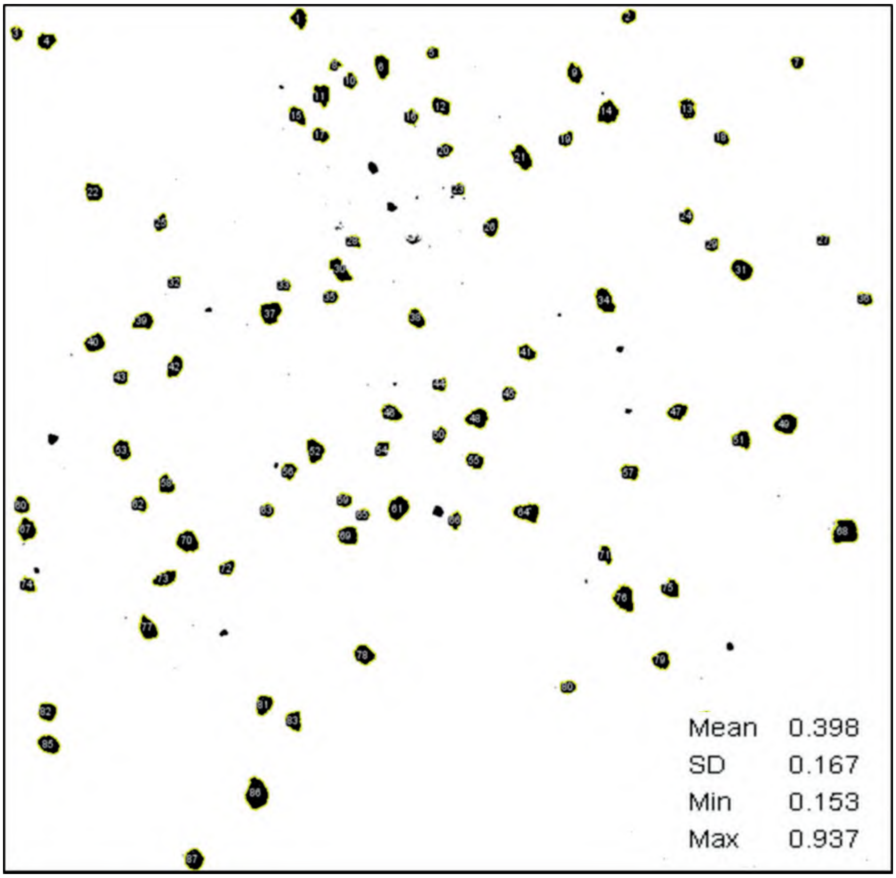

Figure 11. Mineral surface area (in mm^2) calculation using ImageJ.
Şekil 11. ImageJ tabanlı mineral yüzey alanı (mm²) hesaplaması.

The samples were crushed into powder and placed on the plaques. XRD patterns were then obtained and interpreted to identify mineral content. The mineral contents of the powder were calculated by matching peak measurements with the Inorganic Crystal Structure Database (ICSD) 12++ dataset. The XRD results for two sets of mineral assemblages before and after the batch experiments are shown in Figures 16 and 17. PHREEQC software was used to simulate water-rock interaction in the batch experiments. The average mineral surface area, calculated with the ImageJ program, was then multiplied by the mineral content of each mineral to obtain their corresponding surface areas separately.

Equations (5) to (13) provide standard stoichiometric reactions. The CO_2-charged geothermal water reacts with rock minerals in two ways. First, it consumes hydrogen ions that neutralize the acidic gas-charged water, thereby increasing the likelihood of carbonate mineral precipitation as the pH rises. Second, the cations react with dissolved CO_2 to form stable carbonate minerals.

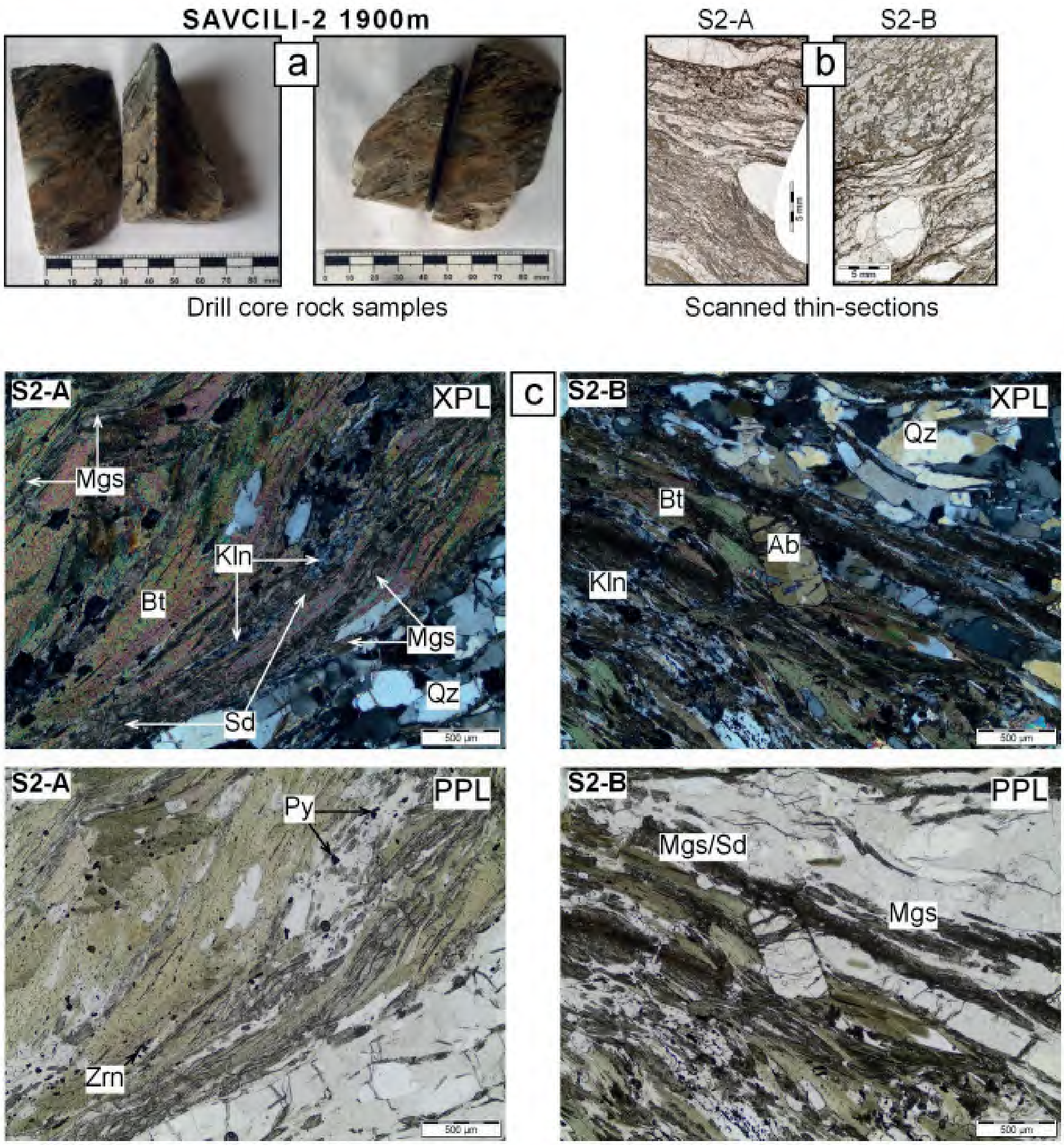

Figure 12. a) Macroscopic view of the core sample taken from 1900 m depth, b) polarized light microscope measurements identified quartz-filled lenses and bands, c) lepidoblastic biotite and granoblastic quartz and albite minerals, and alteration products magnesite (Mgs), siderite (Sd) and kaolinite (Kln) developed between biotite plates. XPL: Double Nicol, PPL: Single Nicol, Mgs: Magnesite, Sd: Siderite, Qz: Quartz, Bt: Biotite, Ab: Albite, Zrn: Zircon Py: Pyrite.

Şekil 12. a) 1900 m derinlikten alınan karot örneğinin makroskobik görünümü b) Polarizan ışık mikroskobu ölçümlerinde kuvars dolgulu lens ve bantlar tanımlanmıştır c) Lepidoblastik biyotit ile granoblastik kuvars ve albit mineralleri, ayrıca alterasyon ürünleri olan manyezit (Mgs), siderit (Sd) ve biyotit lamelleri arasında gelişmiş kaolinit (Kln) mineralleri gözlenmiştir.XPL: Çift nikol, PPL: Tek nikol, Mgs: Manyezit, Sd: Siderit, Qz: Kuvars, Bt: Biyotit, Ab: Albit, Zrn: Zirkon, Py: Pirit.

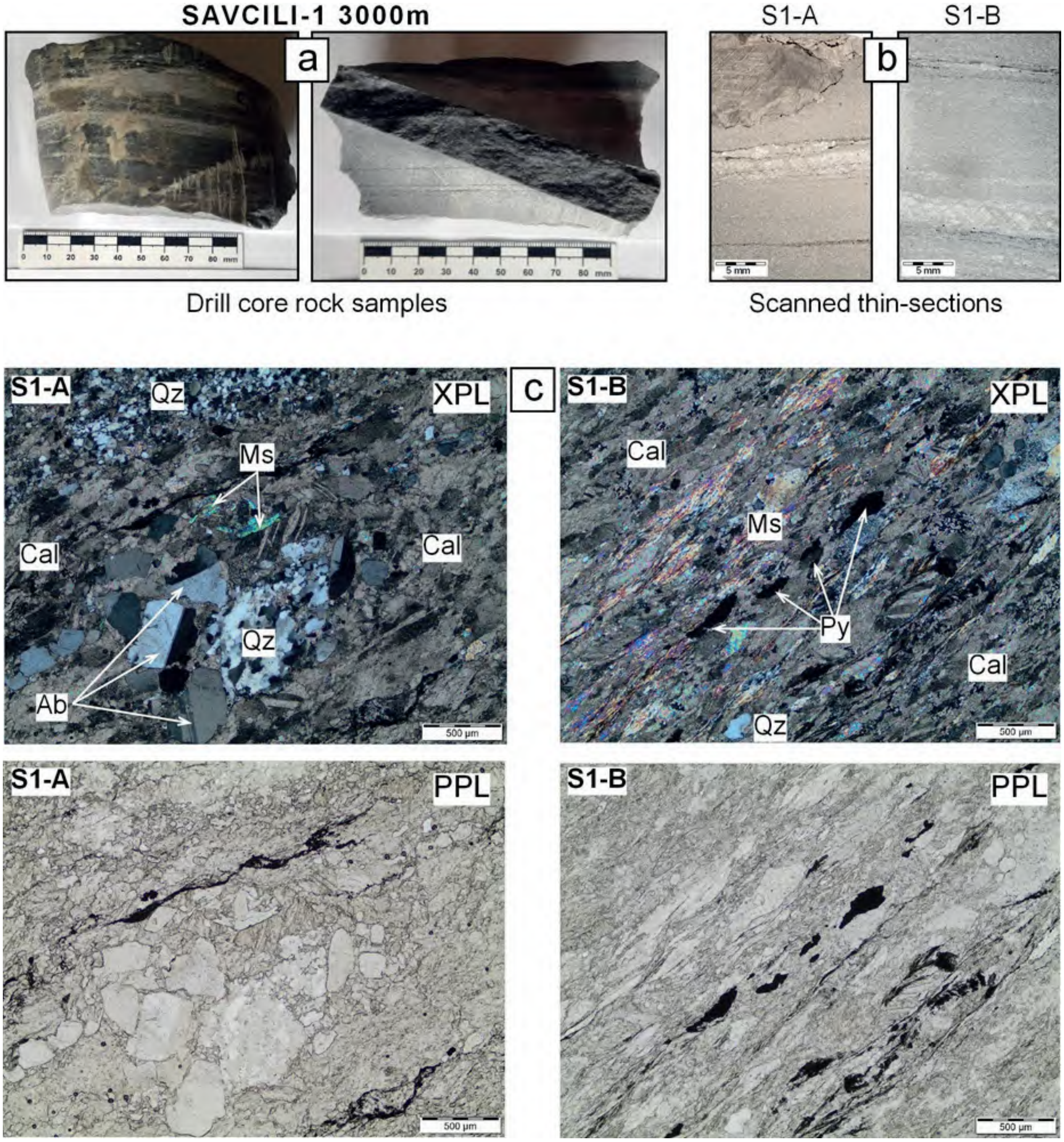

Figure 13. a) Macroscopic view of the core sample taken from 3000 m depth, (b) calcite-filled lens and quartz-filled bands in polarized light microscope measurements, (c) optical microscope views of levels containing granoblastic textured calcites and quartz, albite, muscovite and opaque mineral (pyrite). XPL: Double Nicol, PPL: Single Nicol, Cal: Calcite, Qz: Quartz, Ms: Muscovite, Ab: Albite, Py: Pyrite.

Şekil 13. a) 3000 m derinlikten alınan karot örneğinin makroskobik görünümü b) Polarizan ışık mikroskobu (PLM) incelemelerinde kalsit dolgulu lens ve kuvars dolgulu bantlar gözlenmiştir c) Granoblastik dokulu kalsitlerin yanı sıra kuvars, albit, muskovit ve opak mineral (pirit) içeren seviyelerin optik mikroskop görüntüleri. XPL: Çift nikol, PPL: Teknikol, Cal: Kalsit, Qz: Kuvars, Ms: Muskovit, Ab: Albit, Py: Pirit.

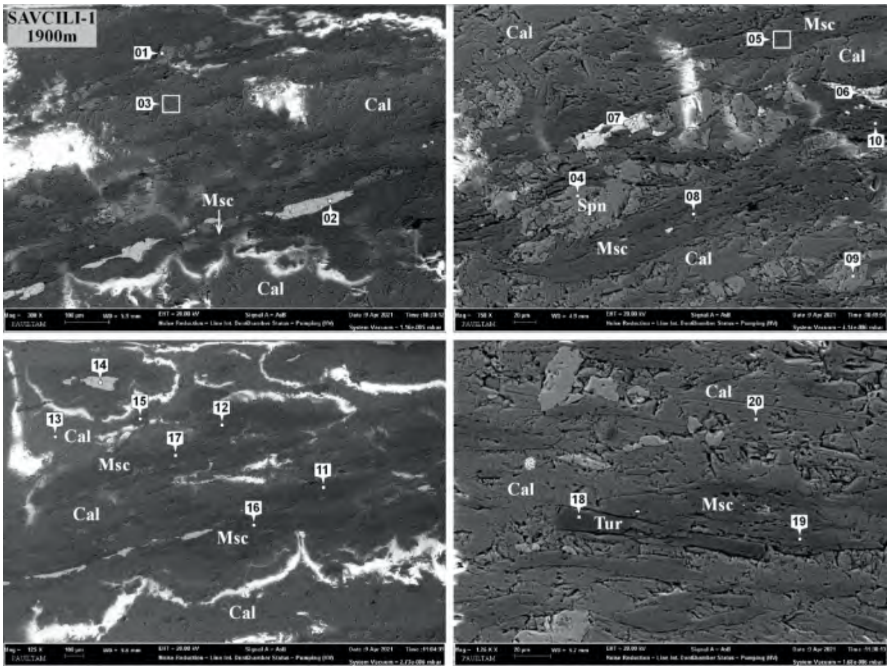

Figure 14. EDX SEM images of rock samples from 1900 m depth.

Şekil 14. 1900 m derinliğindeki kaya örneklerinin EDX-SEM görüntüleri.

Table 5. Chemical formulas of minerals at 1900 m.

Çizelge 5. 1900 m derinliğinde tanımlanan minerallerin kimyasal bileşimleri.

1	Sphene (Titanite)	$CaTiSiO_5$
2	Chloritized biotite	$K_{0.6}(Si_{3.5}Al_{0.5})\ (AI_{2.5}Mg_{2.2}Fe_{0.1})\ O_{10}(OH)_8$
3	Calcite	$CaCO_3$
4	Sphene (Titanite)	$CaTiSiO_5$
5	Phengitic muscovite	$(K_{0.6}Na_{0.2}Ca_{0.1})\ (Si_{3.1}AI_{0.9})\ (AI_{1.5}Mg_{0.8})\ O_{10}(OH)_2$
6	Apatite	$Ca_{5.0}(PO_4)_3(OH)_{0.3}F_{0.3}CI_{0.3}$
7	Pyrite	FeS_2
8	Phengitic muscovite	$(K_{0.6}Na_{0.2}Ca_{0.1})\ (Si_{3.1}AI_{0.9})\ (AI_{1.5}Mg_{0.8})\ O_{10}(OH)_2$
9	Sphene (Titanite)	$CaTiSiO_5$
10	Phengitic muscovite	$(K_{0.6}Na_{0.2})\ (Si_{3.1}AI_{1.0})\ (AI_{1.5}Mg_{0.8})\ O_{10}(OH)_2$
11	Phengitic muscovite	$(K_{0.6}Na_{0.1})\ (Si_{3.1}AI_{0.9})\ (AI_{1.5}Mg_{0.8})O_{10}(OH)_2$
12	Phengitic muscovite	$(K_{0.7})\ (Si_{3.0}AI_{1.0})\ (AI_{1.3}Mg_{1.3}Fe_{0.1})\ O_{10}(OH)_2$
13	Calcite	$CaCO_3$
14	Pyrite	FeS_2
15	Quartz	SiO_2
16	Phlogopite	$(K_{0.7})\ (Si_{3.0}AI_{1.0})\ (AI_{1.0}Mg_{1.7}Fe_{0.1})\ O_{10}\ (OH)_2$
17	Phlogopite	$(K_{0.6}Na_{0.2})\ (Si_{3.0}AI_{1.0})\ (AI_{1.1}\ Mg_{1.4}Fe_{0.1})\ O_{10}(OH)_2$
18	Tourmaline	$NaMg_{3.0}AI_{6.0}(BO_3)_3Si_6O_{18}(OH)_4$
19	Phengitic muscovite	$(K_{0.7})\ (Si_{3.1}AI_{0.9})\ (AI_{1.6}Mg_{0.7}Fe_{0.1})\ O_{10}\ (OH)_2$
20	Calcite	$CaCO_3$

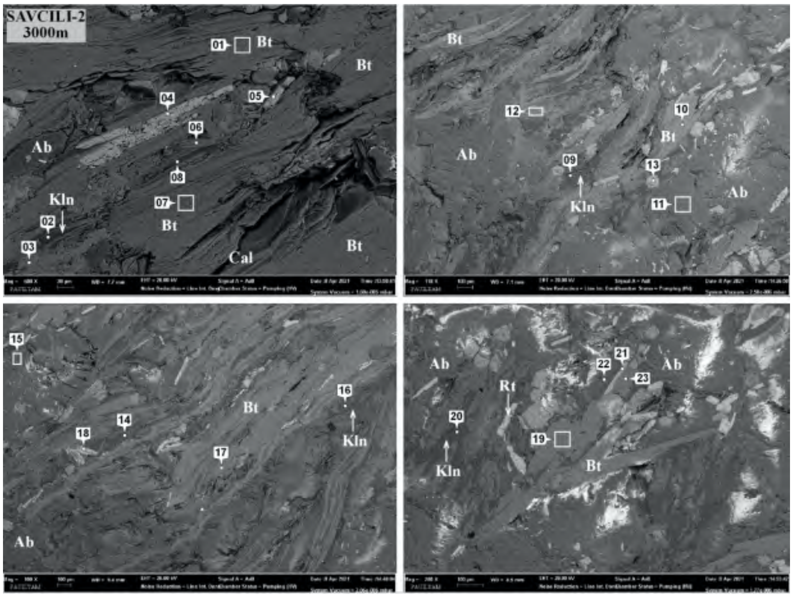

Figure 15. EDX SEM images of rock samples from 3000 m depth.

Şekil 15. 3000 m kaya örneklerinin EDX-SEM görüntüleri.

Table 6. Chemical formulas of minerals at 3000 m.

Çizelge 6.3000 m derinliğinde tanımlanan minerallerin kimyasal bileşimleri.

1	Biotite	$(K_{0.9})(Si_{3.0}AI_{1.0})(Mg_{2.1}Fe_{0.8}AI_{0.2})O_{10}(OH)_2$
2	Kaolinite	$Si_2AI_2O_5(OH)_4$
3	Ferroan Magnesite	$((Mg, Fe)_2CO_3)$
4	Ilmenite	$(Fe^{2+}TiO_3)$
5	Ilmenite	$(Fe^{2+}TiO_3)$
6	Biotite	$(K_{0.7}Na_{0.1})(Si_{3.0}AI_{1.0})(Mg_{2.0}Fe_{0.6}AI_{0.3})O_{10}(OH)_2$
7	Biotite	$(K_{0.8})(Si_{3.0}AI_{1.0})(Mg_{2.1}Fe_{0.6}AI_{0.4})O_{10}(OH)_2$
8	Kaolinite	$Si_2AI_2O_5(OH)_4$
9	Kaolinite	$Si_2AI_2O_5(OH)_4$
10	Biotite	$(K_{0.7})(Si_{3.0}AI_{1.0})(Mg_{2.2}Fe_{0.3}AI_{0.5})O_{10}(OH)_2$
11	Feldspar	$Na_{1.0}AI_{1.0}Si_{3.0}O_8$
12	Calcian magnesian siderite	$(Ca,Mg,Fe)_2CO_3$
13	Apatite	$Ca_{5.0}(PO_4)_3(OH)_{0.3}F_{0.3}CI_{0.3}$
14	Kaolinite	$Si_2AI_2O_5(OH)_4$
15	Feldspar	$Na_{0.9}Ca_{1.0}AI_{1.1}Si_{2.9}O_8$
16	Kaolinite	$Si_2AI_2O_5(OH)_4$
17	Biotite	$(K_{0.9})(Si_{3.0}AI_{1.0})(Mg_{2.1}Fe_{0.8}AI_{0.2})O_{10}(OH)_2$
18	Rutile	TiO_2
19	Biotite	$(K_{0.7})(Si_{3.0}AI_{1.0})(Mg_{2.3}Fe_{0.2}AI_{0.5})O_{10}(OH)_2$
20	Kaolinite	$Si_2AI_2O_5(OH)_4$
21	Ilmenite	$Fe^{2+}TiO_3$
22	Feldspar	$Na_{1.0}AI_{1.0}Si_{3.0}O_8$
23	Biotite	$(K_{0.6}Na_{0.2})(Si_{3.0}AI_{1.0})(Mg_{2.2}Fe_{0.6}AI_{0.3})O_{10}(OH)_2$

The representative reaction for this process is depicted in Equation (5) (Delerce et al., 2023). These cations facilitate the mineralization of CO_2 (g) into biotite, calcite, and kaolinite. In the first mineral assemblage at a depth of 1900 m, the quartz mineral content decreased from 19.4% to 15.3%; magnesite mineral content remained unchanged; kaolinite mineral content increased from 13.2% to 15.7%; and biotite content rose from 3.6% to 4.3%. Dolomite mineral content decreased by half of its initial value, and siderite content fell from 1.5% to 0.4% (Figure 16). In the second mineral assemblage at 3000 m depth, the calcite content increased from 66.6% to 79.1%; the quartz content decreased from 20.3% to 13%; and the muscovite mineral content decreased from 13.1% to 7.9% (Figure 17). Alteration involves the decomposition of primary metamorphic rock and the precipitation of secondary minerals. In the batch experiments, the mineral assemblage remained constant while the abundance of the minerals changed. Equations (6) and (7) represent the carbonation of siderite (Mendoza et al., 2019), while equation (8) describes the reaction of pyrite with water and oxygen to form sulfuric acid. Magnesite carbonation is expressed in equations (9) and (10). Metal cations in the minerals are exchanged for H^+, resulting in the release of metal cations (K^+, Ca^{2+}, Na^+, etc.), and the content of smectite and kaolinite may increase from the retained ions (AI^{3+}, O^{2-}, Si^{4+}) (Mendoza et al., 2019). The hydrolysis of calcium plagioclase feldspar and potassium feldspar is illustrated in equations (11) and (12), and equation (13) depicts the alteration of albite into muscovite. During sampling and handling, CO_2 may degas even with minimal exposure, leading to localized increase in pH within specific microenvironments. This change could temporarily raise the calcite saturation index, promoting its precipitation. Certain mineral phases, especially secondary kaolinite, may have formed during cooling or after the experiment in the drying phase. These are limitations of the experiments.

$$2H^+ + H_2O + (Ca, Mg, Fe, Al)SiO_3 \rightarrow Ca^{2+}, Mg^{2+}, Fe^{2+}, Al^{3+} + H_4SiO_4 \quad (5)$$

$$Fe_3O_4(s) + Fe(s) + 4CO_2(g) \rightarrow 4FeCO_3\ (s) \quad (6)$$

$$Fe_2O_3(s) + Fe(s) + 3CO_2(g) \rightarrow 3FeCO_3\ (s) \quad (7)$$

$$2FeS_2(s) + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + H_2SO_4 + 2H^+ \quad (8)$$

$$Mg^{2+}(aq) + 2HCO_3^-(aq) \rightarrow MgCO_3\ (s) + CO_2\ (g) + H_2O \quad (9)$$

$$Mg(OH)_2 + 2CO_2 \rightarrow Mg(HCO_3)_2 \quad (10)$$

$$KAISi_3O_8 + H^+ + 4.5H_2O \rightarrow 0.5\ Al_2Si_2O_5(OH)_4 + K^+ + 2H_4SiO_4(aq) \quad (11)$$

$$CaAl_2Si_2O_8 + H_2CO_3 + 0.5O_2 \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + CO_3^{2-} \quad (12)$$

$$3NaAlSi_3O_8 + K^+ + 2H^+ \rightarrow KAl_3Si_3O_{10}(OH)_2 + 3Na^+ + 6SiO_2 \quad (13)$$

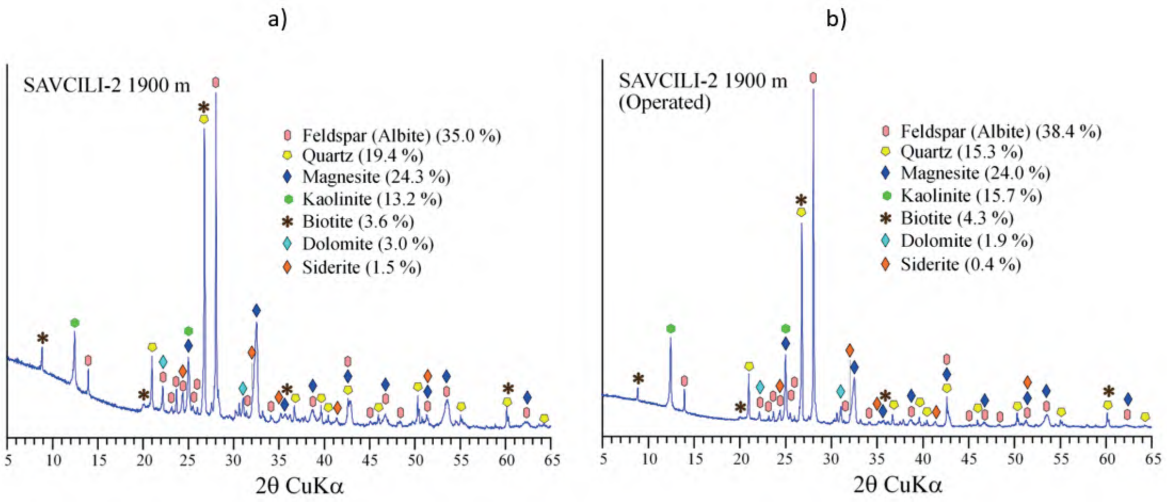

Figure 16. XRD measurements of the core sample taken from 1900 m depth before (a) and after (b) batch experiments.
Şekil 16. 1900 m derinlikten alınan karot örneğinin kesikli deneyleri öncesi (a) ve sonrası (b) XRD ölçümleri.

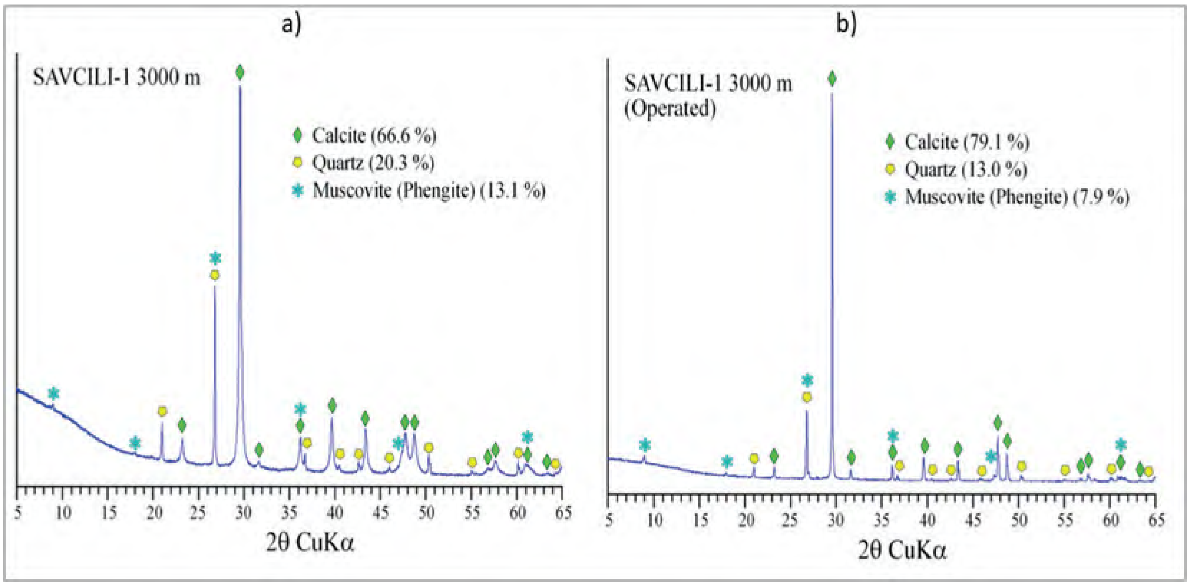

Figure 17. XRD measurements of the core sample taken from 3000 m depth before (a) and after (b) batch experiments.
Şekil 17. 3000 m derinlikten alınan karot örneğinin kesikli deneyleri öncesi (a) ve sonrası (b) XRD ölçümleri.

A PHREEQC code was used to simulate the batch experiment, considering rock surface area, initial moles of minerals, kinetic reaction rates, and activation energy of the minerals. The number of moles and rock surface area for each mineral were calculated using the image processing method and XRD results (Tables 7 and 8). By tuning the kinetic rates and activation energy of the minerals, ion concentrations (SiO_2, Ca^{2+}, Al^{3+}, Cl^-, and Fe^{2+}) were adjusted to match experimental results (Table 7). Concentrations of major elements were aligned with those obtained from experimental results (Figures 18-21). The parameters were consistent with USGS data (Table 9).

It is recognized that calibrating both kinetic rates and activation energy parameters adds flexibility, which, if not carefully constrained, could weaken the model's predictive accuracy. To mitigate this risk, our calibration strategy was informed by literature values, particularly those reported by Palandri and Kharaka (2004), which served as limits for both kinetic rates and activation energies. The tuning process was conducted within these published ranges, prioritizing adjustments to only one parameter (usually the kinetic rate) unless a good match could not be achieved. In such cases, minimal adjustments to the activation energy were made to better align with experimental data while maintaining physical plausibility.

Additionally, the calibration was validated by reproducing multiple elemental concentration trends (e.g., SiO_2, Ca^{2+}, Fe^{2+}), not just a single target variable, which helps reduce the risk of parameter compensation and overfitting.

Table 7**.** Surface area and mole number of mineral assemblages for the rock sample taken from a depth of 1900 m.

Çizelge 7. 1900 m derinliğindeki kaya örneğinde belirlenen mineral topluluklarının yüzey alanı ve mol miktarları.

Minerals	**Mole number**	**Mineral surface area (cm^2)**
Feldspar	0.226	1451.9
Quartz	0.581	804.8
Magnesite	0.518	1008.0
Kaolinite	0.092	547.6
Biotite	0.0149	149.3
Dolomite	0.029	124.5
Siderite	0.023	62.2

Table 8. Surface area and mole number of mineral assemblages for rock sample taken from 3000 m depth.

Çizelge 8. 3000 m derinlikten alınan kaya örneğine ait mineral topluluklarının yüzey alanı ve mol sayısı.

Minerals	**Mole number**	**Mineral surface area (cm^2)**
Calcite	1.118	2578.5
Quartz	0.570	786.0
Muscovite	0.068	507.2

In the first batch experiment, a mineral assemblage comprising rock powder obtained from a core sample taken at a depth of 1900 m was exposed to CO_2-saturated brine for 3 weeks at 95 °C and 10 bar. Due to the constraints associated with sealing the experimental batch tank, the pressure in the experiments was limited to 10 bar. To accurately simulate reservoir conditions, we utilized PHREEQC software. The concentration of major elements was matched with simulations by tuning the activation energy and kinetic reaction rate of minerals.

Table 9. Activation energy and kinetic rate constant to match PHREEQC model with experimental results and USGS values.

Çizelge 9. PHREEQC modelinin deney sonuçları ve USGS değerleriyle uyumlandırılması için kullanılan aktivasyon enerjisi ve kinetik hız sabiti.

	Activation Energy (kJ mol^{-1})		**Kinetic Rate constants (mol m^{-2} s^{-1})**	
	PHREEQC Model	USGS (Palandri & Kharaka, 2004)	PHREEQC Model	USGS (Palandri & Kharaka, 2004)
Quartz	77	87.7	9×10^{-14}	1.023×10^{-14}
Muscovite	22	22	1.404×10^{-13}	2.81×10^{-14}
Pyrite	57	56	8.81×10^{-6}	2.8×10^{-5}
Albite	69	69	2.75×10^{-10}	2.754×10^{-13}
Kaolinite	22	38	6×10^{-11}	1.1×10^{-14}
Dolomite	36	52	6.45×10^{-9}	2.95×10^{-8}
Magnesite	20	23.5	4×10^{-10}	4.5×10^{-10}
Siderite	65	62.7	9×10^{-8}	1.26×10^{-9}
Calcite	20	23.5	9×10^{-9}	1.55×10^{-9}

As seen in Figure 15a, antimony concentration increased from 0.3 ppm to 1.1 ppm. Antimony, a constituent of hydrothermally-formed mineral pangenesis, is often found in the trivalent state as stibnite (Sb_2S_3) (Krupp, 1988). Stibnite is the most abundant mineral for antimony and serves as the primary control over the concentration of antimony in hydrothermal fluid (Olsen et al., 2012). Antimony's sulfur solubility is very sensitive to temperature and pH changes (Erten et al., 2021). In general, stibnite is more soluble in acidic solutions than in basic solutions. This is because the sulfide ion (S^{2-}) is more stable in acidic solutions. In basic solutions, the sulfide ion can react with hydroxide ions (OH) to form insoluble hydroxides. The following reaction shows the oxidation of stibnite in an acidic solution:

$$Sb_2S_3 + 3H_2O + 3O_2 \rightarrow 2Sb\,(OH)_3 + 3H_2S \quad (14)$$

CO_2 dissolution in the geofluid decreases the pH from 9.5 to 7.2. Thus, the reaction in Eq. (14) shifted to the right and increased the antimony concentration.

Al^{3+} decreased from 0.43 ppm to 0.15 ppm (Figure 18b). The source of Al^{3+} was the kaolinite mineral in the rock sample. The precipitation of kaolinite (increasing the mineral content from 13.1% to 15.7%) resulted in a decline in Al^{3+} (Figure 16). Kaolinite is a clay mineral that is relatively insoluble in water. However, its solubility increases as pH decreases. This occurs because the negative charges on the surface of the kaolinite particles are more easily balanced by hydrogen ions (H^+) in acidic solutions (Rao et al., 2011). Kaolinite is also more reactive to acid at lower pH values because acid can break the bonds between the silicon and oxygen atoms in the kaolinite structure. In the experiment, the pH value falls within the alkaline range, which is unfavorable for alkaline solubility.

Table 10. Solubility of kaolinite with respect to pH (Derived from Rao et al., 2011).

Çizelge 10. Kaolinit çözünürlüğünün pH ile ilişkisi (Rao vd., 2011'den türetilmiştir).

pH	Solubility	Reactivity	Stability
Acidic (<4)	High	High	Low
Neutral (4-7)	Low	Low	High
Alkaline (>7)	Very low	Very low	High

Fe^{2+} levels dropped from 0.1 ppm to stabilize at 0.02 ppm (Figure 18c). The Fe^{2+} source in this experiment is attributed to the presence of siderite and biotite minerals. XRD analysis indicated that siderite was dissolving, while biotite precipitated (Figure 16). The solubility of siderite ($FeCO_3$) in water diminishes as pH increases, as siderite is a slightly acidic compound whose solubility is enhanced under acidic conditions (Silva et al. 2002). Equation (15) illustrates the dissolution of siderite in water:

$$FeCO_3\ (s) + H_2O\ (l) + CO_2\ (g) \Leftrightarrow Fe^{2+}\ (aq) + HCO_3^-\ (aq) \quad (15)$$

The solubility of siderite is also affected by the temperature and ionic strength of the solution (Bénézeth et al., 2009). The solubility of siderite decreases with rising temperature and ionic strength.

Table 11. Solubility of siderite with respect to pH (Silve et al., 2002).

Çizelge 11. Siderit çözünürlüğünün pH ile ilişkisi (Silve vd., 2002).

pH	Temperature (ºC)	Solubility (mg L^{-1})
5	25	100
6	25	50
7	25	10
8	25	0.1

Biotite is a mica mineral commonly found in igneous, metamorphic, and sedimentary rocks. It is a sheet silicate mineral, meaning its structure consists of layers of silicon dioxide (SiO_2) sandwiched between layers of aluminum, iron, magnesium, and potassium (Samadi et al., 2021). Generally, biotite dissolves more rapidly in acidic solutions than in basic ones. This is because acidic solutions can more easily break the bonds that hold the minerals together (Bray et al., 2015). The solubility of biotite in water decreases with increasing temperature, as higher temperatures provide more energy for water molecules to break the bonds holding the biotite mineral together (Malmström and Banwart, 1997). In the experiment, the initial temperature was 25 °C, which increased to 95 °C and stabilized throughout the experiment. Thus, biotite exhibited precipitation behavior, resulting in a decrease in Fe^{2+}.

The concentration of Ca^{2+} showed a declining trend during the experiment (Figure 18d). $CaCO_3$ is more soluble in water at lower pH levels, indicating that it dissolves more readily in acidic environments (Hart et al., 2013). This occurs because the carbonate ion (CO_3^{2-}) is more stable in acidic conditions. Additionally, the solubility of Ca^{2+} in water decreases as the temperature rises (Straub, 1932), meaning that less Ca will dissolve in warm water compared to cold. In this experiment, dolomite served as the source of Ca^{2+}. As illustrated in Figure 16, the dolomite concentration dropped from 3.0% to 1.9%. Several factors influence the solubility of dolomite, including temperature, pH, and the presence of other ions, with temperature being the most impactful. Dolomite's solubility in water is influenced by pH; it increases with rising pH levels, suggesting that more dolomite will dissolve in basic solutions due to the carbonate ion (CO_3^{2-}), the primary element in dissolved dolomite, being more stable in such conditions. However, increased temperature results in a decrease in dolomite solubility, as the amount that dissolves in hot water is less than in cold water. The pH in the experiment fell from 9.5 to 7.2 (Figure 19d), which would typically suggest an increase in Ca^{2+} solubility. Nonetheless, the system's temperature elevated from 25 °C to 95 °C, leading to a reduction in Ca^{2+} solubility.

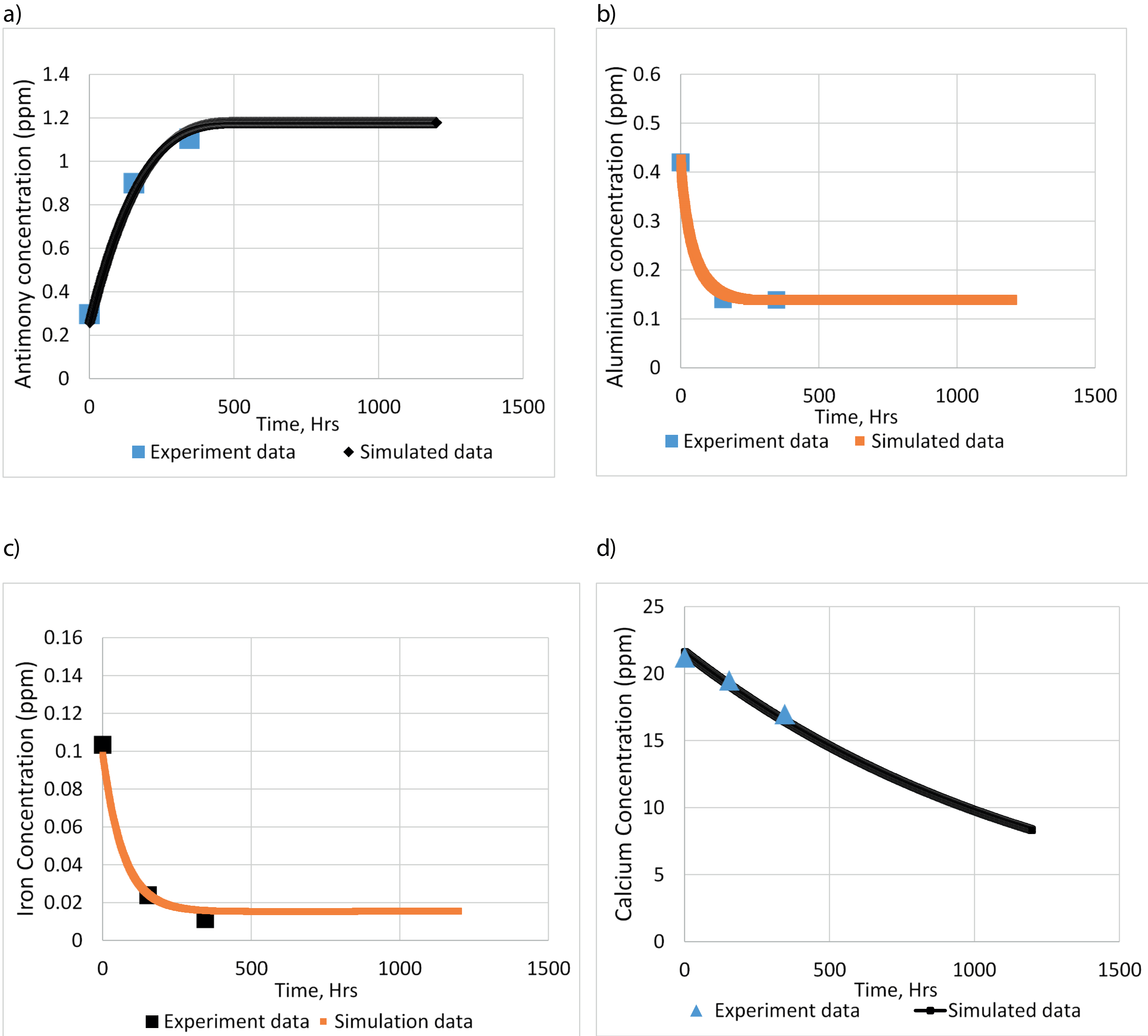

Figure 18. Experimental and simulation results for rock samples taken from 1900 m, a) antimony, b) aluminum, c) Fe^{2+}, d) Ca^{2+}

Şekil 18. 1900 m derinlikten alınan kaya örneklerine ait deney ve simülasyon sonuçları: a) antimon b) alüminyum c) Fe^{2+} d) Ca^{2+}

Silica concentration decreased from 120 ppm to 85 ppm (Figure 19a). The solubility of silica in water is little affected by pH values between 1 and 9, but rises rapidly at pH levels above 9 (Krauskopf, 1956). Consequently, it is not influenced by the pH of the water. The solubility of silica is also impacted by temperature; it increases with rising temperature (Krauskopf, 1956). This is because water molecules can more easily break apart silica molecules at higher temperatures. Additionally, the solubility of SiO_2 is influenced by the presence of other ions in water. For example, the presence of Ca^{2+} can reduce the solubility of SiO_2. This occurs because Ca^{2+} can form complexes with silica molecules, making them less soluble in water (Szymanek et al., 2021).

Mg^{2+} concentration increased from 0.8 to 5 ppm (Figure 19b). The source of magnesium was magnesite and dolomite minerals in the experiment. The presence of magnesite at 1900 m depth was confirmed by consistent XRD peaks and further validated through SEM-EDS spot analyses. The core sample from this depth was classified as a biotite-quartz-albite schist, a typical lithology of the Menderes metamorphic complex. Therefore, the magnesite detected does not have primary igneous origin but is interpreted as a post-metamorphic alteration product formed during low-temperature (<200 °C) hydrothermal processes related to geothermal fluid circulation. This interpretation aligns with previous studies of metamorphic rocks in the region, where magnesite and siderite often occur as pore-filling carbonates or thin alteration bands (Haklıdır et al., 2021; Karamanderesi & Helvaci, 2003; Bozkaya et al., 2024). Magnesite content decreased from 24.3% to 24% and dolomite mineral content decreased from 3.0% to 1.9% (Figure 16).

The Cl concentration remained constant, stabilizing around 145 ppm (Figure 19c). The solubility of chloride ions in water is unaffected by pH. Cl ions are negatively charged, while pH measures the concentration of H^+ in a solution. Solubility of Cl is influenced by temperature, but not by pH (Musa & Hamoshi, 2012).

In the second batch experiment, a mineral assemblage comprising rock powder obtained from a core sample taken from a depth of 3000 m was exposed to CO_2-saturated brine for 3 weeks at 95 °C and 10 bar. The mineral content of the rock sample is shown in Figure 17.

Mg^{2+} concentration showed an increasing trend (Figure 20a). The solubility of Mg^{2+} increases with rising pH, indicating that more Mg^{2+} will dissolve in basic solutions. This occurs because the hydroxide ion (OH^-), which is the primary form of Mg^{2+} in water, is more stable in basic solutions (Nishiki et al., 2023). As depicted in Figure 20d, pH decreased from 9.5 to 7.1 with CO_2, then increased slightly to 7.5. This increased Mg^{2+} concentration.

Aluminum concentration showed a declining behavior (Figure 20b). The solubility of aluminum hydroxide decreases with increasing temperature and ionic strength (Feng et al., 2008). The system's temperature was increased from 25 ºC to 95 ºC, and the lack of kaolinite in the system caused a decrease in aluminum concentration.

The solubility of calcium carbonate ($CaCO_3$) in water increases as the pH decreases, indicating that more $CaCO_3$ will dissolve in acidic solutions (Hart et al., 2013). This occurs because the carbonate ion (CO_3^{2-}) is more stable in acidic environments. The solubility of calcium (Ca^{2+}) in water decreases as the temperature rises (Straub, 1932). In the experiment, the Ca^{2+} concentration increased significantly (Figure 20c). This is attributed to the increasing acidity of the brine (Figure 20d). Consequently, a decrease in the calcite mineral content of the assemblage was expected by the end of the experiment. However, XRD results indicate an increased trend (Figure 20). This behavior is likely due to the sudden pressure drop in the system, which led to $CaCO_3$ precipitation.

Silica concentration decreased from 105 to 67 ppm (Figure 21a). Consequently, it is unaffected by the pH of water. The solubility of silica is influenced by temperature. Specifically, the solubility of silica increases with rising temperature (Krauskopf, 1956). This occurs because water molecules can more easily break apart silica molecules at higher temperatures. Additionally, the solubility of silica is affected by the presence of other ions in the water. For example, the presence of Ca^{2+} can reduce the solubility of silica. This happens because Ca^{2+} can form complexes with the silica molecules, making them less soluble in water (Szymanek et al., 2021). A significant increase in Ca^{2+} concentration probably decreased silica solubility.

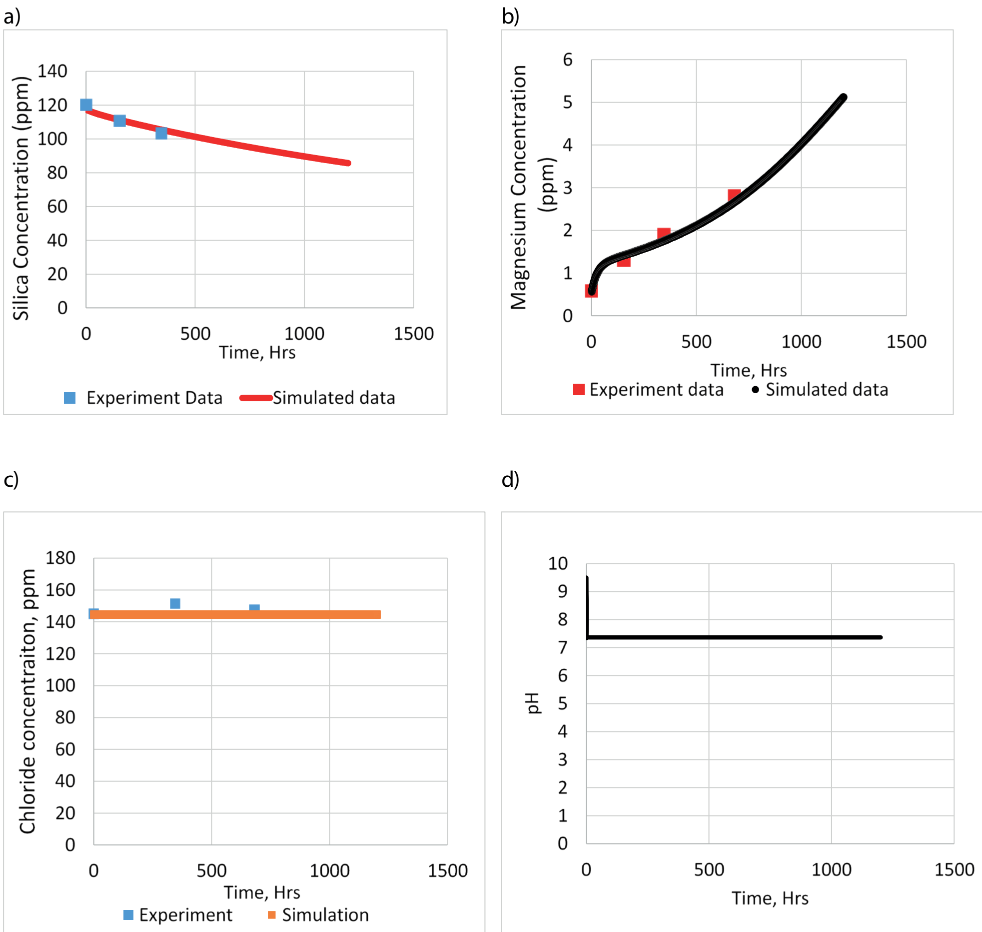

Figure 19. Experimental and simulation results for rock samples taken from 1900 m, a) SiO_2, b) Mg^{2+}, c) Cl^-, d) pH.
Şekil 19. 1900 m derinlikten alınan kaya örneklerine ait deney ve simülasyon sonuçları: a) SiO_2 b) Mg^{2+} c) Cl^- d) pH.

The solubility of Fe^{2+} in water is influenced by the pH of the solution. Iron dissolves more readily in acidic solutions compared to neutral or alkaline solutions. This increased solubility occurs because the iron atoms in acidic environments are more inclined to lose electrons, resulting in the formation of positively-charged ions (Fe^{2+} or Fe^{3+}). These ions are significantly more soluble in water than their neutral or negatively-charged counterparts (Liu & Millero, 2002). Lowering the pH from 9.5 to 7.1 raised iron solubility from 0.165 to 0.205 ppm (Figure 18b).

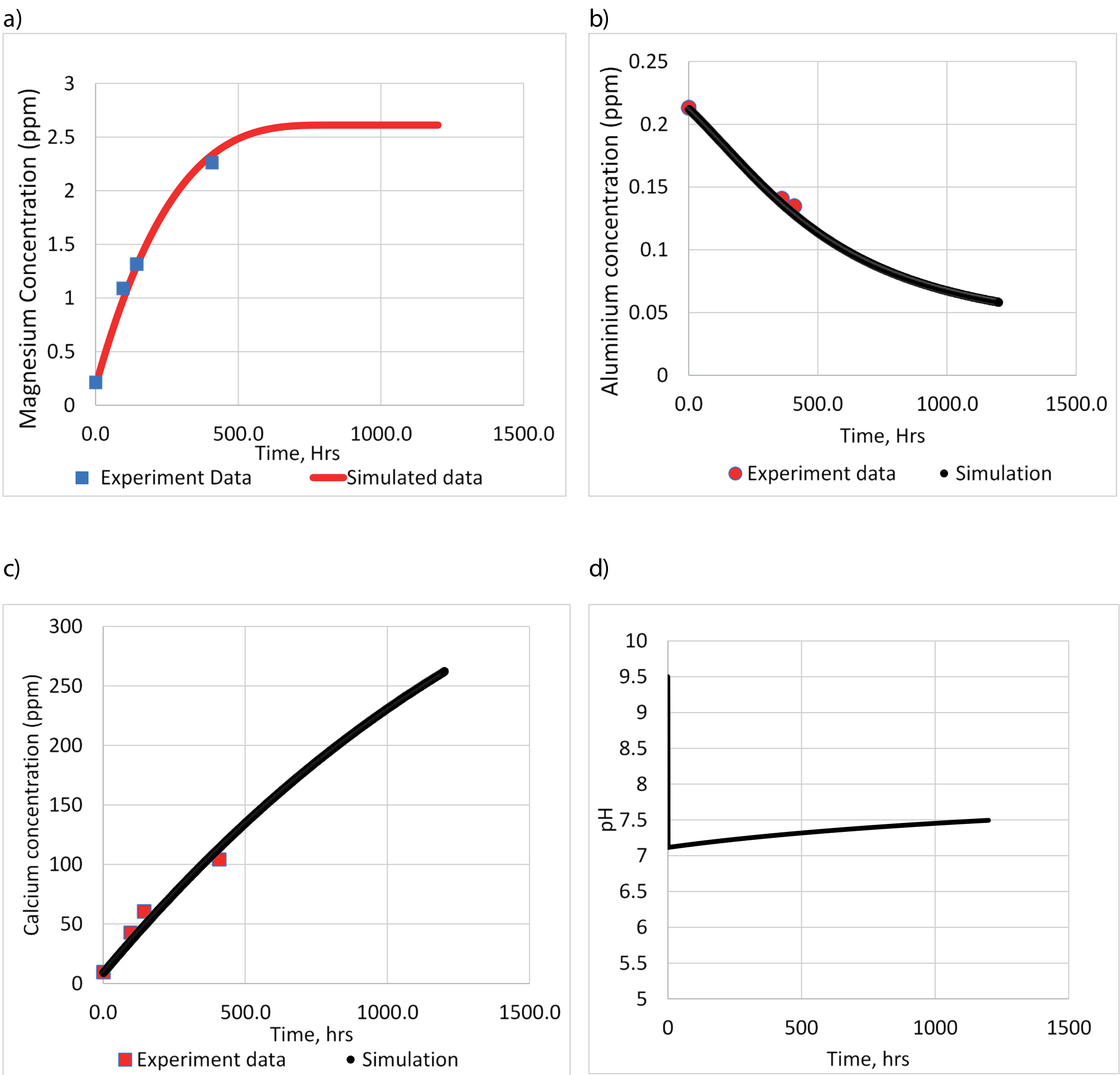

Figure 20. Experimental and simulation results for rock samples taken from 3000 m, a) magnesium, b) aluminum, c) Ca^{2+}, d) pH.

Şekil 20. 3000 m derinlikten alınan kaya örneklerine ait deney ve simülasyon sonuçları: a) magnesium b) aluminum c) Ca^{2+} d) pH.

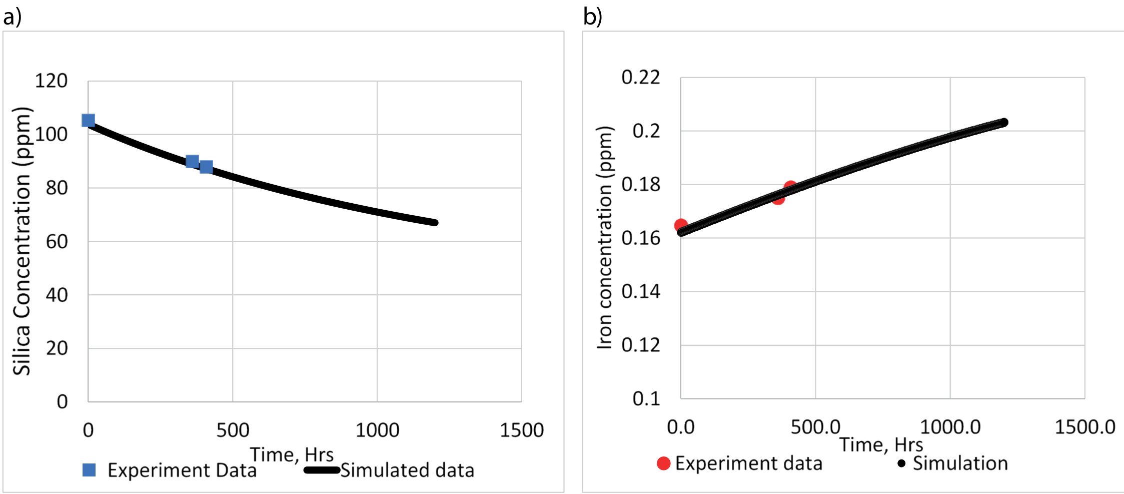

Figure 21. Experimental and simulation results for rock samples taken from 3000 m, a) silica, b) iron.
Şekil 21. 3000 m derinlikten alınan kaya örneklerine ait deney ve simülasyon sonuçları:a) silika b) demir

XRD results showed that rock samples involved specific alterations, such as siderite, magnesite, muscovite, kaolinite, dolomite, quartz, biotite, and feldspar (albite).

In the CO_2-saturated geofluid-rock interaction for the first mineral assemblage (1900 m), quartz, magnesite, dolomite, and siderite minerals exhibited a dissolution trend, while feldspar, kaolinite, and biotite demonstrated precipitation behavior. In the batch experiment with the second mineral assemblage (3000 m), calcite displayed precipitation behavior. The increasing acidity of the fluid favors calcite dissolution, as confirmed by Figure 20c, which indicates an increase in Ca^{2+} concentration. The rise in calcite content is likely associated with the experimental procedure; as the interaction is completed, the system is discharged to collect minerals for rock analysis following the experiment. During the discharge process, CO_2 is released, leading to calcite precipitation. Quartz and muscovite had dissolution trends. The pH of the solution decreased from 9.5 to 7.2 due to CO_2 dissolution in the brine. The decreasing pH caused a decline in silica in both batch experiments because solubility changes rapidly when pH exceeds 9.

In the studied batch experiments, the mineral assemblage remained the same while the abundance of the minerals changed. The study showed that the presence of cations such as Ca^{2+}, Al^{3+}, and Fe^{2+} promoted the precipitation of CO_2 as carbonates. The results of the batch experiments matched those of the PHREEQC results. The parameters adjusted for these matches were activation energy and kinetic reaction rates of the minerals. The tuning values of the parameters were in accord with USGS data for quartz, muscovite, pyrite, magnesite, siderite, and calcite. Discrepancies were observed for albite, kaolinite, and dolomite.

In the fluid-rock interaction experiments, the primary CO_2 trapping mechanism was identified as solubility trapping rather than mineralization. The results of solubility trapping can be found in Aydin and Akin (2023). CO_2 was measured using a gas flowmeter and alkalinity tests. The maximum gas content was determined to be 0.45% by weight under the experimental conditions. Siderite, magnesite, and calcite are the main minerals associated with CO_2 mineralization. As the $CaCO_3$ content of minerals was analyzed, 8.87 g of CO_2 was mineralized. Meanwhile, 40.5 g of CO_2 was dissolved in the geothermal brine.

Solubility trapping, although beneficial in the short- to medium-term due to its quick kinetics and high capacity under reservoir conditions, is essentially reversible. Pressure drops can cause CO_2 to degas, posing potential risks for remobilization and even leakage over time. Reinjection of waste brine is an industrial practice used to maintain the sustainability of geothermal production and reservoir pressure. Continuous re-injection can help mitigate long-term reservoir pressure declines. There are also specialized techniques for gas leakage monitoring, such as distributed temperature sensing (DTS), which utilizes fiber optics in the wellbore to detect gas leaks (Merey & Aydin, 2025), and remote sensing technologies like InSAR for monitoring ground subsidence and tilting during gas injection. Akın et al. (2025) observed soil CO_2 fluxes surrounding the faults in Kızıldere field before and after the demo-pilot gas injection at the nearby well. No significant variations were detected in shallow groundwater composition or soil CO_2 fluxes throughout the different phases of the injection.

It is important to note that the batch experiments were conducted under relatively lower pressure and temperature conditions compared to in situ conditions due to laboratory limitations. As a result, the kinetic rates and mineral stability observed in this study may differ from those under actual reservoir conditions, where elevated temperature and pressure significantly influence geochemical processes. While the findings provide valuable insights into water-rock interaction trends, they should be interpreted as indicative rather than fully representative of in situ behavior. Future studies will aim to incorporate high-pressure and high-temperature experiments to simulate reservoir conditions more accurately.

Although core samples were taken from the Kızıldere geothermal reservoir, the geothermal brine for the batch experiments was sourced from the Alaşehir field. This choice was mainly due to operational convenience, as the experimental setup was located in Alaşehir, allowing easy access to fresh geothermal brine from a nearby injection well. Additionally, previous hydrochemical analyses indicate that the geothermal fluids of Kızıldere and Alaşehir have similar Na-HCO_3-type water chemistry (Haklıdır & Sengun, 2020). Thus, using Alaşehir brine was appropriate for simulating water-rock interactions under representative conditions. However, we recognize that using brine directly from Kızıldere would have provided a more site-specific understanding of fluid-rock interactions. This limitation is acknowledged, and future studies will include parallel experiments with brine from the Kızıldere reservoir to enable more detailed comparisons.

CONCLUSION

This study offers a comprehensive understanding of the geochemical changes and mineral reaction kinetics during CO_2 sequestration in Paleozoic metamorphic rocks, utilizing a detailed experimental and simulation approach.

Our investigations underscore the efficiency and stability of CO_2 sequestration through solubility trapping mechanisms compared to mineral trapping under the studied conditions. Importantly, the high cation concentrations present in the metamorphic rocks of the Kızıldere geothermal reservoir positively contribute to the CO_2 trapping potential. These geochemical insights are critical for optimizing CO_2 sequestration strategies in similar geological settings worldwide.

Crucially, batch experiments conducted at 95 °C and 10 bar revealed that a substantial portion of CO_2 (0.45% by weight, corresponding to 40.5 grams in 9 liters of brine) was trapped as dissolved gas, highlighting the dominance of solubility trapping over mineral trapping, where only 8.87 grams of CO_2 were mineralized. This predominance of solubility trapping emphasizes the importance of solution geochemistry in optimizing CO_2 sequestration strategies.

The experiments also indicated potential challenges associated with SiO_2 precipitation, notably as the pH decreased from 9.5 to 7.2, conditions were unfavorable for SiO_2 dissolution. Therefore, it is critical to maintain the injection temperature above the silica saturation temperature to mitigate SiO_2 precipitation.

Furthermore, a comparison between various rock depths indicates that the reservoir rock at a depth of 3000 m may be more conducive to CO_2 injection. This phenomenon can be attributed to the enhanced injectivity potential resulting from the interactions between CO_2-saturated brine and rock at this specific depth.

Future research should aim to broaden the experimental parameters to encompass different pressures and temperatures; thereby, more accurately simulating the natural conditions of geothermal reservoirs. Moreover, extended reaction studies are essential to comprehend the sustainability and long-term ramifications of mineral alterations on the efficacy of CO_2 trapping. Such insights will be critical in refining our understanding of geological CO_2 storage mechanisms and improving the reliability of these methods in mitigating atmospheric CO_2 levels; hence, contributing to global climate change mitigation strategies.

Nomenclature

k_1 is the specific rate constant in mol/mol^2/sec at 25 ºC,

k_2 is the specific rate constant at a specified temperature in Kelvin (T_K),

R is the gas constant, 8.3145 J/mole,

E is the activation energy for each mineral, J/mole,

SR is the saturation ratio (ion activity/equilibrium constant) with transition-state theory,

m_0 is the initial moles of the kinetic reactant,

A_0 is the initial surface area of mineral in meter^2,

V is the solution volume in contact with A_0 in liters; concentration is in mg/L.

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Derleme / *Review*

Artificial Intelligence in Water Consumption Forecasting: A Systematic Review

Su Tüketimi Tahmininde Yapay Zekâ: Sistematik İnceleme

Gülsüm AŞIKSOY[1*], Hüseyin GÖKÇEKUŞ[2]

[1] *Artificial Intelligence Engineering Department, Near East University, Nicosia, Mersin 10, Türkiye*

[2] *Faculty of Civil and Environmental Engineering, Near East University, Nicosia, Mersin 10, Türkiye*

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ABSTRACT

Predicting water consumption is crucial for the sustainable management of water resources and for solving the world's water problems. Water is the subject of numerous studies as it is essential for the survival of all living beings. Artificial intelligence, machine learning and conventional statistical methods have been used in these studies. This article provides a comprehensive overview of the research about AI applications for water consumption predictions. The study was conducted using articles published between 2019 and 2024, retrieved from academic databases such as SpringerLink, IEEE Xplore and Scopus. The analyzed literature was categorized based on water studies in relation to the algorithms used to predict water consumption. The study also investigated the advantages, disadvantages and difficulties of artificial intelligence methods used in water consumption estimation studies. The results show that the performance of Long Short-Term Memory models is better than other methods. Nevertheless, data quality and availability are limiting factors. This study examines recent advances in predicting water consumption using AI-based methods and identifies potential areas for further research in this field.

Keywords: Artificial intelligence, machine learning, water demand management, water forecasting

ÖZ

Su tüketiminin tahmin edilmesi, su kaynaklarının sürdürülebilir bir şekilde yönetilmesi ve dünya genelindeki su sorunlarının çözülmesi açısından hayati öneme sahiptir. Su, tüm canlıların yaşamı için vazgeçilmez olduğundan, uzun süredir birçok çalışmanın odağında yer almıştır. Bu çalışmalarda yapay zekâ, makine öğrenmesi ve geleneksel istatistiksel yöntemler kullanılmıştır. Bu makale, su tüketimi tahmininde yapay zekâ uygulamalarına dair mevcut araştırmaları kapsamlı bir şekilde incelemektedir. Çalışma, 2019 ile 2024 yılları arasında yayımlanmış ve SpringerLink, IEEE Xplore ve Scopus gibi akademik veri tabanlarından elde edilmiş makaleler üzerinden yürütülmüştür. İncelenen literatür, su tüketimini tahmin etmek için kullanılan algoritmalara göre sınıflandırılmıştır. Ayrıca, su tüketimi tahmin çalışmalarında kullanılan yapay zekâ yöntemlerinin avantajları, dezavantajları ve karşılaşılan zorluklar da değerlendirilmiştir. Elde edilen sonuçlar, Uzun Kısa Süreli Bellek (LSTM) modellerinin performansının diğer yöntemlere kıyasla daha iyi olduğunu ortaya koymaktadır. Bununla birlikte, veri kalitesi ve erişilebilirliği sınırlayıcı faktörler arasında yer almaktadır. Bu çalışma, yapay zekâ tabanlı yöntemlerle su tüketimi tahminine yönelik son gelişmeleri incelemekte ve bu alandaki gelecekteki araştırmalar için potansiyel yönleri vurgulamaktadır.

Anahtar Kelimeler: *Yapay zeka, makine öğrenmesi, su talebi yönetimi, su tüketimi tahmini.*

Sorumlu yazar / *Corresponding author:* gulsum.asiksoy@neu.edu.tr

INTRODUCTION

Water consumption has increased significantly with the growing world population and advancing technology (Piasecki et al., 2018). Water resources are critical elements for the economic development of a country or region. As worldwide population growth accelerates in parallel with economic globalization, water scarcity has become a significant obstacle to socio-economic development in many countries (Chen et al., 2021). Improving the efficiency of water management, creating a holistic framework that integrates the social, economic and environmental dimensions in harmony with the natural water cycle, conserving water as a strategic resource, and effectively planning and utilizing resources are crucial steps in sustainable development policies. Raising consumer awareness of water stewardship is also an essential part of this process (Kavurucu et al., 2022)

Water is a finite and critical natural resource that significantly influences economic and social development. Modeling and forecasting about the use of this scarce resource is crucial to effectively meet current and future demand (Dong et al., 2013). Accurately predicting trends in water use will enable the development of strategies that align resource management processes with sustainability goals and support immediate and long-term needs (Willmott, & Matsuura, 2005).

Predicting water use is important for managing resources, averting water-related crises, and ensuring the equitable distribution of available resources. For managers, these water use prediction models compensate for the time invested in developing strategies, planning for the future, and managing resources efficiently (Rustam et al., 2022). These models also help to assess the impact on water use patterns of climatic changes, population growth, the scale of economic activities and the expansion of urban settlements (Rustam et al., 2022; Yu et al., 2019).

To date, conventional methods for modeling water consumption patterns have used statistical analysis (Bejarano et al., 2019). Political, economic, and sociological factors have traditionally been modeled using linear trends. In many cases, the inclusion of water consumption is only sometimes linear or modular. This has created a need to use more advanced approaches (Ribeiro et al., 2021). Recently, there has been growing interest in artificial intelligence (AI) and other machine learning-based technologies as new tools to improve water consumption forecasting. Advantages of these methods lie in their ability to process large amounts of data, recognize non-linear dependencies, and respond flexibly to the demands of the changing environment (Pourmousavi et al., 2022).

This article provides a systematic review of the literature about the use of AI applications in predicting water consumption. By analyzing the performance of different algorithms, characteristics of data types, and model limitations based on literature reports from related fields, this study exposes the current state of affairs in this area and identifies where there may be gaps for further investigation. Ultimately, the study aims to present an overarching view that is useful for both academia and practice.

METHODOLOGY

The main objective of this study is to systematically evaluate the artificial intelligence methods used in predicting water consumption, discuss the challenges encountered and highlight the opportunities for future research. To ensure transparency and reliability, a rigorous methodology was applied based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009).

Databases and Screening Process

In this study, three academic databases were searched to find studies that used artificial intelligence methods to estimate water consumption: SpringerLink, Scopus, and IEEE Xplore.

During the search process, keywords such as “artificial intelligence”, “machine learning”, “deep learning”, “water consumption”, “water usage”, “water demand forecasting”, and “water demand prediction” were used to find studies and examine the role of artificial intelligence techniques in water consumption forecasting.

The search strategy was developed using a combination of keywords related to artificial intelligence and water demand forecasting. Boolean operators and wildcard characters were used to expand the search scope and capture all relevant literature. The Boolean search expression applied was as follows:

(“Artificial Intelligence” OR “Machine Learning” OR “Deep Learning”) AND (“Water Consumption” OR “Water Usage” OR “Water Demand”) AND (“Forecasting” OR “Prediction”).

This approach ensured the inclusion of studies that used various terminology to describe AI-based water consumption prediction models. Keywords were searched in the title, abstract, and keyword fields to maximize retrieval of relevant studies.

Inclusion and Exclusion Criteria

Inclusion and exclusion criteria are summarized in Table 1.

The inclusion criteria for our study focused on selecting research that utilized artificial intelligence techniques for forecasting water consumption. Studies incorporating real-world and simulated water consumption data were also considered for analysis. The studies needed to be published between 2019 and 2024 and written in English, as these were key selection criteria. Studies using statistical methods other than artificial intelligence techniques for water consumption forecasting research were not included. In addition, duplicate studies, book chapters and conference abstracts and papers whose full texts could not be accessed were excluded. These criteria were applied to maintain focus and methodological rigor in the study.

Table 1. Inclusion and exclusion criteria for systematic review.
Çizelge. Sistematik derleme için dahil etme ve hariç tutma kriterleri.

Inclusion Criteria	Exclusion Criteria
Studies using artificial intelligence techniques for water consumption forecasting.	Studies using statistical methods other than AI-based prediction techniques.
Studies using real-world water consumption data as well as simulated data.	Duplicate studies or those with inaccessible full text.
Studies published between 2014 and 2024.	Studies with inaccessible full text.
Studies written in English.	Book chapters, conference abstracts.

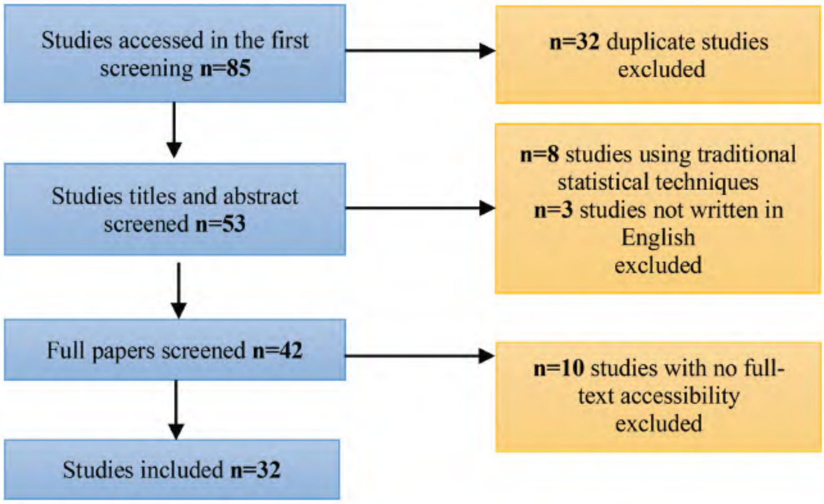

Figure 1. PRISMA flow diagram for selection process (n represents the number of studies).
Şekil 1. Çalışma seçme sürecine ait PRISMA Akış Şeması (n, çalışma sayısını temsil etmektedir).

The process for selecting relevant publications is illustrated in detail in the PRISMA flow chart in Figure 1. The initial search yielded 85 articles. After removing 32 duplicates, 53 studies remained. Of these, 8 were excluded for using traditional statistical methods and 3 for not being written in English. Another 10 studies were excluded due to lack of full-text access. Finally, 32 studies were included in the systematic analysis.

Data Reliability and Bias Assessment

For the reliability of the study, the articles were evaluated individually by two independent researchers, and then a consensus was reached on whether each study should be included. In addition, criteria such as the impact factors of the journals in which the articles were published, the number of citations of the studies, and the potential for direct application of the studies in the environmental and climatic context were analyzed in detail. Thus, it was ensured that the articles included in the systematic review were only those that met high scientific standards and were relevant to the study's objectives.

Table 2 provides a summary of the 32 studies included in this systematic review. The studies are classified according to the region in which they were conducted, the AI methods used, the dataset characteristics, the performance metrics, and the results obtained.

RESULTS

This systematic review examined 32 studies about predicting water consumption using artificial intelligence (AI) techniques. This review comprehensively analyzes the capabilities, challenges, and practical applications of AI in predicting water consumption by integrating insights from recent research, data from Excel datasets, and critical references.

Table 2. Reviewed studies about artificial intelligence based water consumption forecasting.
Çizelge 2. Yapay zekâ tabanlı su tüketimi tahminine ilişkin incelenen çalışmalar.

References	**Region**	**AI Methods**	**Dataset**	**Performance Metrics**	**Results**
El Hanjri et al. (2023)	Morocco	LSTM, ARIMA	Residential and institutional water usage data	RMSE	Achieved RMSE 5.60 m³ and 89% correlation, demonstrating strong predictive performance.
Cao et al. (2023)	China	LSTNet, AutoStG, ASTGCN	Hourly water consumption (1, 3, 6, 12, and 24 hours)	RMSE, MAE, RSE	ASTGCN model reached RMSE 566.4 m³, MAE 377.7 m³, and 96.4% accuracy.
Monjardin et al. (2020)	Philippines	ANN	Socioeconomic, rainfall, temperature.	R-value	ANN achieved a strong correlation of R=0.97013 between actual and predicted water usage.
(Rustam et al. 2022)	-	RF, DT, ET, LR, SVM, ADA, CNN, GRU	Kaggle and GitHub datasets for water consumption	F1, RMSE, MAE, MSE, R^2	Delivered 96% accuracy for water quality prediction.
Huang et al. (2023)	China	SAE, BPNN	Hourly water usage data	MAPE, RMSE	BPNN achieved MAPE of 2.31% and RMSE of 320 m³/hour, indicating stable short-term prediction.
Boudhaoui & Wira (2021)	France	ML, LSTM, BPNN	Hourly water consumption data	RMSE	LSTM predicted next hour consumption with minimal error, showing strong long-term dependency learning.
Farah, et al. (2019)	France	ANN	Hourly data from AMR meters	RMSE, R^2	High correlation (R^2 = 0.902) and accurate predictions for restaurant water consumption patterns.
Tzanes et al. (2023)	Tilos Island	Fuzzy Clustering Algorithm	Simulated water usage clusters	MAE, RMSE	Clustering reduced MAE by 29%, improving short-term water usage predictions.
Cao et al. (2024)	China	SSA-CNN-BigRU	Raw water consumption data	MAE, RMSE, R^2	Achieved 94.73% accuracy for urban water demand predictions.
Liu et al. (2023)	China	STL-ADA-LSTM	Daily water demand data for two facilities	MAE, MAPE, MSE, RMSE, R^2, AIC	Strong trend and seasonal forecasting for water facilities, but performance varied by data type.
Kim et al. (2023)	South Korea	DNN, LSTM	Daily water demand data from Gurye station	CC, NRMSE, F1	LSTM achieved 0.95 correlation and NRMSE of 8.38, demonstrating excellent performance.

Table 2. Devamı

Çizelge 2. Continued.

References	**Region**	**AI Methods**	**Dataset**	**Performance Metrics**	**Results**
Yan et al. (2022)	China	Spatial Clustering, MLP	Spatial clustering and water usage data	MAE, RMSE	Hybrid CNN-bilSTM improved deterministic and probabilistic predictions by up to 26.7%.
Wang et al. (2023)	China	ESN	Residential and agricultural water demand data	-	SN predicted water demand for 2025, with estimates varying by economic and price scenarios.
Zheng et al., (2022)	China	NARX Neural Network	Smart meter data	MAE, MAPE, RMSE	RS-NARX outperformed standard NARX models, providing better accuracy and stability.
Gutiérrez et al., (2020)	Mexico	AHN	Water flow sensor data	RMSE	Achieved a low RMSE of 2.49 liters/hour, demonstrating reliable predictions.
Oyebode (2019)	South Africa	DE with Feedforward Neural Networks	Weather, socioeconomic, and water usage data	Pearson correlation, Information gain	Feature selection techniques improved prediction accuracy over the baseline.
Ribeiro et al. (2021)	Brazil	SVR, Ridge Regression, Gaussian Proc.	Water usage data from two cities in Paraná	RMSE, MAE, MAPE	Effective multi-step forecasting using seasonal-trend decomposition and ML models.
Bejarano et al. (2019)	USA	Sparse Gaussian CRFs, LSTM, RNN	Building-level water usage data	RMSE, MAE	SwAP system improved RMSE and MAE by 50% and 44%, respectively, over baselines.
Oyebode & Ighravw (2019)	South Africa	DE, CG-SVM, ES, MLR	Real-world data from Ekurhuleni City	R^2, MAPE, RMSE	Evolutionary computing techniques effectively enhanced predictive performance for urban water demand.
García-Soto et al. (2024)	Spain	KNN, RF, SARIMA	10-minute interval time series data from Murcia City	MAE, MAPE, RMSE, R^2	Deep learning model outperformed other techniques like RF, KNN, and SARIMA in prediction accuracy.
Görenekli & Gülbağ (2024)	Turkiye	ANN, RF, SVM, GBM	Historical data for 5000 water subscribers	R^2, MSE, RMSE, MAE	GBM achieved the highest performance with $R^2 = 0.881$.
Pourmousavi et al. (2022)	Iran	MLR, SVR, RF Regression	Annual residential water consumption in Isfahan	MAE, RMSE, MSE, R^2	MLR achieved 96% accuracy with <11% error; SVR achieved 95% accuracy with <13% error

Table 2. Devamı
Çizelge 2. Continued.

References	Region	AI Methods	Dataset	Performance Metrics	Results
Shirkoohi et al. (2021)	Canada	ANN, GA, ARIMA	Water consumption data from two cities -5 years and 23 months	RRMSE, Nash-Sutcliffe efficiency (E), MAPE	High accuracy for residential water consumption forecasting with <13% error rates.
Sajjanshetty et al. (2023)	Philippines	ANN	Income, rainfall, temperature, climate data	R-value, RMSE	ANN achieved high R-value of 0.97013 and low RMSE of 2.3463, effectively predicting Metro Manila water demand.
Al-Ghamdi, et al. (2022)	Saudi Arabia	ANN with PSO	Historical water demand and climate data (2004-2018)	RMSE	Hybrid ANN-PSO model achieved high daily water demand forecasting accuracy by optimizing hyperparameters.
Du et al. (2020)	China	Markov-modified ARIMA	Daily water consumption data from monitoring points	Relative Prediction Error (RE), R^2, RMSE	Markov-modified ARIMA corrected prediction errors and improved future forecasts over standard ARIMA.
Boudhaouia & Wira, (2022)	France	PR, NAR, SVR, MLP, LSTM	Internet-based platform providing daily water usage data	RMSE	NAR model achieved precise daily consumption predictions for residential (5 liters) and industrial facilities (23 liters).
Bhushan (2022)	India	LSTM, ARIMA	Sensor data	MAPE	LSTM achieved ~60% accuracy, outperforming ARIMA's 49%, demonstrating effectiveness with limited sensor data.
Gao et al. (2020)	China	UWM-ID	Water usage, weather, economic data, and water prices	MAE, RMSE	UWM-ID outperformed RF, MLP, and LSTM with 40%, 33%, and 20% improvements, respectively, across various test scenarios.
Zubaidi (2020)	-	Slime mould algorithm (SMA-ANN)	Monthly urban water consumption and climate data	MAE, MARE, MSE, R^2	The results highlighted the importance of data pre-processing to prepare the stochastic pattern of dependent and independent variables and to select the best scenario of independent variables.
Said et al. (2021)	Malaysia	DLNN-MLP, DLNN-CNN, DLNN-LSTM	Historical data based on the SIBU Division in Sarawak	RMSE	DLNN-LSTM (RMSE:0.051) can make decent predictions for water consumption time series despite being inferior to SARIMA (RMSE:0.183).

Artificial Intelligence Techniques and Algorithms in Studies

The most commonly used artificial intelligence models reviewed in this study were identified as Long Short-Term Memory (LSTM) models and Artificial Neural Networks (ANN), respectively.

Long Short-Term Memory (LSTM) Models

The studies analyzed in this review displayed the exceptional capabilities of LSTM models, mainly when applied to datasets with strong temporal dependencies. LSTM was developed by Hochreiter and Schmidhuber as a specialized type of recurrent neural network architecture (1997). The LSTM algorithm is highly effective in automatically extracting features from time series data and learning complex nonlinear relationships (Yu et al., 2019). Traditional recurrent neural networks (RNNs) produce effective results when working with data from the recent past. In contrast, LSTM models achieve more impactful outcomes with longer term data, such as months or years. In other words, LSTM models excel in utilizing large and complex datasets to deliver more accurate results. For instance, in the study by Kim et al. (2023) an LSTM model applied to water consumption data collected from different time intervals demonstrated exceptional performance, achieving low root mean square error (RMSE) values and high accuracy rate of 95%.

This study demonstrates that LSTM models were effectively utilized in both standalone (El Hanjri et al., 2023) and hybrid approaches (Boudhaouia & Wira, 2021; Kim et al., 2023; Liu et al., 2023). Standalone LSTM models learn from historical data to provide reliable predictions, while hybrid models combine LSTM with other algorithms to enhance accuracy (Boudhaouia & Wira, 2021). For instance, integrating LSTM with Particle Swarm Optimization (PSO) significantly reduced prediction error rates (Al-Ghamdi et al., 2022). However, it was also observed that LSTM models require substantial computational power to process large datasets and involve challenges related to generalization in certain scenarios (Bhushan, 2022).

Artificial Neural Networks (ANNs)

ANNs excel at identifying complex patterns and relationships within data, making them highly effective for tasks where traditional, non-AI models may struggle (Monjardin et al., 2020). Among these networks, methods such as Convolutional Neural Networks (CNN) (Cao et al., 2023), Feedforward Neural Networks (FFNN) (Oyebode, 2019), and Backpropagation Neural Networks (BPNN) (Huang et al., 2023) have been successfully implemented as standalone models for predicting water consumption.

Multilayer Perceptrons (MLP) were applied to predict urban water consumption based on meteorological data (Gao et al., 2020) and spatial clustering and water usage data (Yan et al., 2022).

In the studies included in this article, ANN models achieved high accuracy levels in predicting water consumption for different user groups. Specifically, when environmental factors such as rainfall, humidity, and evaporation are integrated into the models, these models produce more precise prediction results (Sajjanshetty et al., 2023).

Hybrid models

This systematic review examined studies utilizing individual and hybrid models of two or more AI applications. For instance, Al-Gamdi et al. (2022) applied the hybrid ANN-PSO model, while Zubaidi et al. (2020) developed and utilized a Slime Mold Algorithm (SMA)-ANN. Boudhaouia and Wira's (2022) study explored how ANN models can be combined with the SARIMA model to enhance water consumption predictions. The SARIMA and MLP hybrid models improved prediction accuracy by 4.6% compared to SARIMA alone, illustrating the enhanced performance of hybrid approaches.

Rustam et al. (2022) employed a novel machine learning approach to predict water quality and water consumption using various models, including deep learning models such as Random Forest (RF), Decision Tree (DT), Extra Trees (ET), Logistic Regression (LR), Support Vector Machine (SVM), and AdaBoost (ADA). As a result of the study, they achieved an accuracy of 0.96 in water quality prediction, outperforming existing studies in this field.

Said et al. (2021) found that integrating deep learning neural networks (DLNN) with MLP, CNN or LSTM models produced more accurate water consumption predictions compared to using these models individually. Furthermore, clustering algorithms and decision trees, when integrated with ANNs and SVM, were shown to enhance the accuracy of water demand predictions (Görenekli & Gülbağ, 2024; Oyebode & Ighravwe, 2019). Piasecki et al. (2018) compared the predictive performance of ANN and Multiple Linear Regression (MLR) models for estimating daily water consumption based on previous water usage and humidity records. The findings revealed that the ANN approach slightly outperformed the MLR model, achieving lower mean absolute percentage error (MAPE) value when an additional explanatory variable (humidity) was included in the ANN model. In summary, hybrid approaches can overcome the limitations of individual models, leverage the strengths of diverse methodologies, and provide deeper insights into the relationships between variables.

Performance Indexes

Performance indexes are statistical tools necessary to determine the predictive capability of an artificial intelligence model. They identify the error between the actual (measured) values and the values predicted by the model. In this way, they show how close the model's predictions are to the actual values. The indexes most commonly used in the studies included within the scope of this work are RMSE, MAPE, and R^2, respectively (Cao et al., 2024; Farah et al., 2019; Huang et al., 2023, Rustam et al., 2022).

RMSE is used to minimize the difference between actual values and predicted values. A low RMSE value indicates that the model's performance is excellent. MAPE, on the other hand, identifies the difference between actual and predicted values and expresses it as a percentage. The smaller the MAPE value, the better the model's accuracy (Willmott & Matsuura, 2005). The R^2 index measures the fit of a model to the data. It determines the relationship between the inputs (independent variables) and outputs (dependent variables). A high R^2 value indicates the model's accuracy and compatibility with the data (Willmott, 1981).

Pros, cons, and challenges of AI models

AI models can make accurate and reliable predictions for water consumption only by analyzing large datasets (Kim et al., 2013). These models are capable of identifying hidden patterns and trends in water consumption data. Moreover, AI models can be continuously updated with new data, enabling them to improve their performance over time (Huang et al., 2023).

In cases of missing data or uncertainty, hybrid and fuzzy models are highly effective tools for water consumption prediction (Yan et al., 2022). Thanks to their flexibility, fuzzy models can produce consistent predictions even when there are slight changes in input values. Additionally, they generate quick results with minimal processing time (Tzanes et al., 2023).

However, some models, such as ANN and DLNN, require large training and validation data. Additionally, these models may struggle with generalization, limiting their performance (Gao et al., 2020). While hybrid models like BSA-ANN and FFBP-ANN can improve predictions, they often have relatively slow processing times (Farah et al., 2019; Zubaidi et al., 2020). Although BPNN can accurately predict water consumption, it lacks generalization capability (Huang et al., 2023). Similarly, RF can become slow and less effective when a large number of trees are involved (Pourmousavi et al., 2022).

In summary several key considerations must be addressed to achieve highly accurate results with AI models for water consumption assessments. For example, researchers need to provide transparent information about the variables used in the models, the quality of the data, and the training process. Such openness will not only enhance the reliability of the studies but also reduce the likelihood of redundant research efforts.

DISCUSSION AND CONCLUSION

This systematic review highlights the role of AI in predicting water consumption and synthesizes recent studies from a methodological perspective. Unlike previous reviews, it identifies model-specific limitations, highlights gaps in application contexts, and integrates insights from hybrid modelling approaches while emphasizing the importance of developing low-cost and generalizable AI solutions.

Among the reviewed techniques, LSTM models achieved successful results in scenarios requiring time series analysis. This is because they accurately model long-term trends (such as annual increases and decreases) and seasonal fluctuations.

Indeed, this situation was clearly seen in case studies in the literature. For example, Kim et al. (2023) achieved an accuracy rate of up to 95% with an LSTM model trained with water consumption data collected at different time intervals. Similarly, Gao et al. (2020) reported that even under limited sensor data conditions, the LSTM model significantly outperformed the ARIMA model, which remained at 49% accuracy, with a prediction accuracy of approximately 60%.

The fact that LSTM provides such high accuracy is considered an important scientific finding.

These reliable predictions can be integrated into decision support systems in the field of water management, allowing resource planning to be optimized and proactive measures to be taken against demand fluctuations. In this way, the strategic steps required for the sustainable management of water supply-demand balance can be supported with more accurate data.

However, despite high accuracy rates for metrics such as RMSE and MAPE, these models face significant challenges due to their reliance on large data sets and extensive computational resources.

LSTM models typically require large amounts of data to make accurate predictions, which can negatively impact the performance of the models if sufficient and high-quality data is not available (El Hanjri et al., 2023). In addition, their complex algorithms require significant computing power (Boudhaouia & Wira, 2021). Working with large or complex datasets often requires robust hardware for training and operation. This can be a barrier to the widespread adoption of LSTM models.

Hybrid models are emerging as a highly effective and promising solution to overcome the limitations of single methods (Oyebode, 2019). Their ability to achieve high accuracy and adaptability results from combining the strengths of different AI models (Faiz & Daniel, 2023). However, hybrid models also have certain disadvantages. Problems such as slow processing times and increased complexity highlight the need to optimize hybrid models (Yan et al., 2022).

One of the key findings of this study is the critical importance of data quality and accessibility. When faced with incomplete or biased data, many models need help with generalization. Furthermore, most complex AI models are perceived as "black boxes", which makes their adoption by water management decision makers difficult (Wei et al., 2024).

LIMITATIONS AND FUTURE STUDIES

This systematic review has some limitations. First, the studies reviewed are limited to those published between 2019 and 2024. Studies about AI-based water consumption estimation published outside these years are not included in this review. Secondly, the data used in the individual studies comes from different regions or contexts. These differences make it difficult to directly compare the results of the studies. Furthermore the articles included in this systematic review used different evaluation techniques, such as water consumption or water costs, to measure the performance of the AI models. This diversity makes it difficult to determine which technique is most effective. Fourthly, all studies included in the review were written in English. Papers in other languages were not included in the research. Finally, this review does not include a meta-analysis due to the high heterogeneity of datasets, performance metrics, and study designs among the selected articles.

Future research should address several key aspects to bridge the gap in AI-based water use prediction studies and improve the studies in this field. The most important of these is the quality of the data to be used in the studies and the accessibility of the data. Good quality and sufficient data improve the training and output performance of the AI model. In addition, more work can be done on the integration of new AI algorithms. The development of interdisciplinary collaborations, e.g. between oceanographers, AI experts and legislators, will help to develop new models that will meet needs in the real world. Furthermore, more research on models that require low computational costs, i.e. less computing power and data, will help AI to be used effectively in areas such as sustainable water management. Although this review included studies from diverse application domains (e.g., residential, industrial, and urban settings), a detailed sub-analysis by domain was not conducted. Future studies may benefit from categorizing research based on application context to uncover domain-specific trends and challenges.

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Araştırma Makalesi / *Research Article*

Sustainable Water Management in the İzmir Bay Sub-Basin: An Evaluation of Water Resources with the WEAP Model

İzmir Körfezi Alt Havzasında Sürdürülebilir Su Yönetimi: WEAP Modeli ile Su Kaynaklarının Değerlendirilmesi

Hazal DURMUŞ[1], Şebnem ELÇİ[2]

[1] *İzmir Institute of Technology, Department of International Water Resources, 35430-İzmir, Türkiye*
[2] *İzmir Institute of Technology, Department of Civil Engineering, 35430-İzmir, Türkiye*

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ABSTRACT

Water is essential for life. It plays a critical role in sustaining both natural ecosystems and urban environments. However, the sustainability of this vital resource is increasingly at risk due to growing pressures. The İzmir Bay sub-basin, located in the semiarid western region of Türkiye, holds significant economic, ecological, and social importance. However, the region's water resources are facing significant challenges due to rapid urbanization, population growth, and the impacts of climate change, with vulnerability expected to increase in the future. This study employs the Water Evaluation and Planning (WEAP) model to evaluate water potential, address domestic and agricultural water demands, and explore management strategies for sustainability of the region. The research first examines available water resources that supply water to eleven districts in the former metropolitan area of İzmir province (Balçova, Bayraklı, Bornova, Buca, Çiğli, Gaziemir, Güzelbahçe, Karabağlar, Konak, Karşıyaka, and Narlıdere) within the sub-basin. Population projections for the region up to 2050 were also estimated to understand water demand. Additionally, favorable and unfavorable scenarios were developed based on projected changes in temperature, precipitation, and flow rates under the RCP4.5 scenario. These projections utilized MPI-ESM-MR and HadGEM2-ES, both of which are state-of-the-art global climate models. Three scenarios —reference, optimistic, and pessimistic— representing varying climatic and hydrological conditions were analyzed using the WEAP model. Findings indicate a sharp rise in water demand, reaching 318.25 hm³ by 2050 in the reference scenario, while the pessimistic scenario forecasts the highest demand at 381.59 hm³. Unmet demand could rise dramatically under pessimistic conditions, reaching 160.9 hm³ by 2050. This emphasizes the urgent need for mitigation strategies. The optimistic scenario demonstrates that proactive policies and climate resilience measures can prevent shortages and provide water balance. Without strategic interventions, İzmir Bay's water security will remain at risk. Forward-looking policies and effective management are essential to ensure equitable and sustainable water distribution in the face of growing demand and climate change pressures.

Keywords: climate change scenarios, İzmir Bay sub-basin, WEAP model, water resources management

Corresponding author / Sorumlu yazar*:* hazaldurmus@iyte.edu.tr

ÖZ

Su, hem doğal ekosistemlerin hem de kentsel yaşamın sürdürülebilirliği için hayati bir rol oynamaktadır. Ancak, artan baskılar nedeniyle bu önemli kaynağın sürdürülebilirliği giderek daha fazla risk altına girmektedir. Türkiye'nin yarı kurak batı bölgesinde yer alan İzmir Körfezi alt havzası, ekonomik, ekolojik ve sosyal açıdan büyük bir öneme sahiptir. Ancak, hızlı kentleşme, nüfus artışı ve iklim değişikliğinin etkileri nedeniyle su kaynakları ciddi tehditlerle karşı karşıyadır ve bu kırılganlığın gelecekte artması beklenmektedir. Bu çalışma, İzmir Körfezi alt havzasında su potansiyelini değerlendirmek, kentsel ve tarımsal su taleplerini analiz etmek ve sürdürülebilir yönetim stratejileri geliştirmek amacıyla Su Değerlendirme ve Planlama (WEAP) modelini kullanmaktadır. Araştırma, alt havzada yer alan ve eski İzmir metropol alanına dâhil olan on bir ilçeye (Balçova, Bayraklı, Bornova, Buca, Çiğli, Gaziemir, Güzelbahçe, Karabağlar, Konak, Karşıyaka ve Narlıdere) su sağlayan mevcut kaynakları incelemektedir. Ayrıca, bölge için 2050 yılına kadar su talebini anlamak adına nüfus projeksiyonları oluşturulmuştur. Çalışmada, RCP4.5 iklim senaryosu kapsamında MPI-ESM-MR ve HadGEM2-ES küresel iklim modelleri kullanılarak olumlu ve olumsuz senaryolar geliştirilmiştir. Referans, İyimser ve Kötümser olmak üzere üç senaryo, WEAP modeli ile analiz edilmiştir. Sonuçlar, su talebinin 2050 yılına kadar referans senaryoda 318.25 hm^3'e, kötümser senaryoda ise 381.59 hm^3'e ulaşacağını göstermektedir. Olumsuz koşullarda, karşılanamayan su talebinin 160.9 hm^3'e çıkabileceği öngörülmektedir. Bu durum, acil önlem alınması gerektiğini vurgulamaktadır. İyimser senaryo, proaktif politikaların ve iklim direncini artıran önlemlerin su kıtlığını önleyebileceğini ve su dengesi sağlayabileceğini göstermektedir. Stratejik müdahaleler olmadan, İzmir Körfezi'nin su güvenliği tehdit altında kalmaya devam edecektir. Artan talep ve iklim değişikliği baskıları karşısında, uzun vadeli su sürdürülebilirliği için ileriye dönük politikalar ve etkin su yönetimi büyük önem taşımaktadır.

Anahtar kelimeler: *iklim değişikliği senaryoları, İzmir Körfezi alt havzası, WEAP modeli, su kaynakları yönetimi*

INTRODUCTION

Water resources are essential for sustaining life, economic development, and ecological balance. In the 21st century, the world is facing some major challenges such as rapid population expansion, unrestrained urban sprawl, and the ever-increasing impacts of climate change. These pressures are threatening the availability and sustainability of water resources worldwide.

Water has always been the paramount element in human endeavors within urban environments. The world is predominantly becoming a more urbanized environment, characterized by human settlements and dominant economic activities. According to the United Nations (UN), more than half of the world's population resides in urban areas today, and this number is expected to increase by 68% to reach 2.5 billion people by the year 2050 (UN, 2019). As the world undergoes these ongoing increases in population, industrialization, and urban development, the unavoidable consequence is a heightened risk of water scarcity and deficiencies in the resilience of water systems. However, the challenges of water scarcity and managing urban water effectively have become an increasingly challenging and complex undertaking (Negahban-Azar & Mosleh, 2021). Therefore, a shift from conventional supply-driven water management approaches to more sustainable and integrated strategies is required (Yılmaz & Harmancıoğlu, 2010). To ensure long-term water security, it is necessary to assess the impacts of climate change and socio-economic factors on water resources, to be able to take necessary measures and implement effective management strategies.

The İzmir Bay sub-basin, a highly significant region for İzmir, is especially vulnerable to these pressures. Expanding urban areas, industrial growth, and agricultural activities are causing increasing demand for water, while the region's supply remains heavily dependent on climatic conditions and seasonal variations. Currently, major dams supplying drinking and domestic water to İzmir, such as Balçova, Tahtalı and Gördes Dams, are experiencing historically low water levels due to prolonged droughts. This decline in water availability is a manifestation of growing climate change effects and raises concerns about the region's future water security. With the alterations in climatic and hydrological patterns, water shortages may tend to worsen. This has led to the need to analyze the region's water resources related to these impacts.

To address these challenges, researchers increasingly rely on hydrological models to analyze and predict the potential effects of climate change and land use change on water systems. Although modeling involves inherent uncertainties, it serves as a valuable tool for simulating, assessing, and understanding complex hydrological processes and future water availability (Hussain, 2023).

One of the most widely used tools for integrated water resources management was developed by the Stockholm Environment Institute (SEI) in 1989, the Water Evaluation and Planning (WEAP) system. The WEAP system enables researchers to model water resources, simulate various future scenarios, and assess the impacts of climate change and socio-economic factors on water availability (Yates et al., 2005). Its ability to represent both the physical and spatial characteristics of water resources makes it a valuable tool for assessing several scenarios based on "what if?" questions, such as "What if population growth and economic development patterns change? What if reservoir operating rules are altered? What if groundwater is more fully exploited?" (SEI, 2015). From small watersheds to large river basins, the WEAP model has been successfully applied at various scales to support decision-making and policy development in the context of water resources management (Hussain, 2023).

Several studies proved the effectiveness and credibility of WEAP in assessing water resources and addressing water management challenges. Mourad and Alshihabi (2016) assessed current and future water supply and demand in Syria until 2050, under various scenarios, including climate change, regional cooperation, and conflict with the WEAP model. According to their findings, climate change and regional tensions could worsen water scarcity, while cooperation and advanced technologies could help close the supply-demand gap. Also, the urgent need for additional water supplies was emphasized. Mounir et al. (2011) optimized water allocation among competing sectors, such as agriculture, industry, and domestic use, in the Niger River basin, by employing WEAP. Their study demonstrated the challenges of water management in a region with diverse ecosystems and increasing industrial growth. They also emphasized the importance of integrated resource planning. Comair et al. (2012) analyzed the vulnerability of groundwater resources under changing climate patterns and increasing water demand by applying WEAP to the Jordan River basin. Their findings indicate that all aquifers supplying water to Amman are at risk of depletion, and the need for sustainable management strategies was stressed. Hamlat et al. (2013) used WEAP to evaluate water resource management scenarios in western Algeria, a region affected by prolonged droughts and declining water quality. The results revealed that neither domestic nor agricultural water demands were fully met, and the necessity of improved allocation policies and demand management strategies to mitigate future shortages was reinforced.

In Europe, Blanco-Gutiérrez et al. (2011) used WEAP in the Middle Guadiana basin, Spain, to simulate large-scale irrigation systems under normal and drought conditions by integrating hydrological and economic models. Their findings highlighted the value of scenario-based planning for optimizing water allocation and policy evaluation.

In Türkiye, the WEAP model has been applied to analyze regional water resource challenges under changing climatic and socio-economic conditions. For example, Yılmaz and Harmancıoğlu (2010) evaluated different hydrological scenarios to determine the effects of climate variability on agricultural water demand in the Gediz River basin by using WEAP. The region's vulnerability to drought and the need for adaptive water management policies were demonstrated in their findings. More recently, Karahan and Elçi (2023) conducted a basin-based WEAP analysis in the Tahtalı-Seferihisar sub-basin. Their study examined multiple pressures on water resources and different future scenarios to predict water supply-demand balances until 2050. Their results indicated significant unmet demand even under optimistic conditions, and the necessity of long-term planning and sustainable resource allocation was reinforced.

Although previous studies examined water resources in nearby basins (Yılmaz & Harmancıoğlu, 2010; Karahan & Elçi, 2023), a comprehensive water budget analysis has not been conducted for the İzmir Bay sub-basin. Understanding the current and future state of water resources in this sub-basin will contribute to sustainable management and policy development. Therefore, this study aims to fill this gap by evaluating the water potential in the İzmir Bay sub-basin using the WEAP model. Three distinct —reference, optimistic and pessimistic— scenarios under different climatic conditions were developed, and water availability in the sub-basin by the year 2050 was estimated. By simulating these scenarios, this study aims to provide insights into the potential impacts of climate change and population dynamics on the future availability of water resources in the İzmir Bay sub-basin. It also aims to provide adaptive policy recommendations for the sustainable management of water in the region.

STUDY AREA

İzmir is a metropolitan city located on the western coast of Türkiye, situated between 37°45' and 39°15' north latitudes and 26°15' and 28°20' east longitudes, covering an area of 12,012 km² (Republic of Türkiye İzmir Governorship, 2024). It has a semiarid Mediterranean climate, characterized by dry and hot summers and mild, rainy winters. As of 2024, it is the third-largest city in Türkiye with a population of 4,493,242 people (Turkish Statistical Institute, 2024).

According to the last available report of the General Directorate of İzmir Water and Sewerage Administration (IZSU), approximately 307 hm³ of water was supplied to İzmir province in total in 2023. Of this total, 61.22% was derived from groundwater resources, while 38.78% was obtained from surface water resources (IZSU, 2023).

The study area is located within the İzmir Bay sub-basin, one of the five sub-basins of the Küçük Menderes hydrological basin, as shown in Figure 1. The study area represents the inner part of the Bay region and covers eleven central districts of İzmir—Balçova, Bayraklı, Bornova, Buca, Çiğli, Gaziemir, Güzelbahçe, Karabağlar, Konak, Karşıyaka, and Narlıdere—making it the most densely populated sub-basin. It covers 11.73% of the Küçük Menderes basin with an area of approximately 817 km². As reported by the Republic of Türkiye Ministry of Forestry and Water Affairs (MFWA), the annual average precipitation estimated by the Thiessen polygon method is 670 mm. The annual average surface water potential is 126 hm³/year (MFWA, 2016a). There are also many streams within the boundaries of the sub-basin, shown in Figure 2.

In the groundwater recharge assessment for the İzmir Bay sub-basin, the annual average recharge was estimated at 70.5 hm³/year, of which only 52.5 hm³/year is considered the safe groundwater recharge limit (MFWA, 2016a). According to the Küçük Menderes Basin Master Plan Final Report, 70 wells were drilled by the State Hydraulic Works within the sub-basin, while an additional 865 wells have been constructed by local users. Notably, groundwater resources are being heavily overexploited, significantly exceeding the sustainable recharge limit, with total annual groundwater consumption reported as 171.5 hm³/year (MFWA, 2016a).

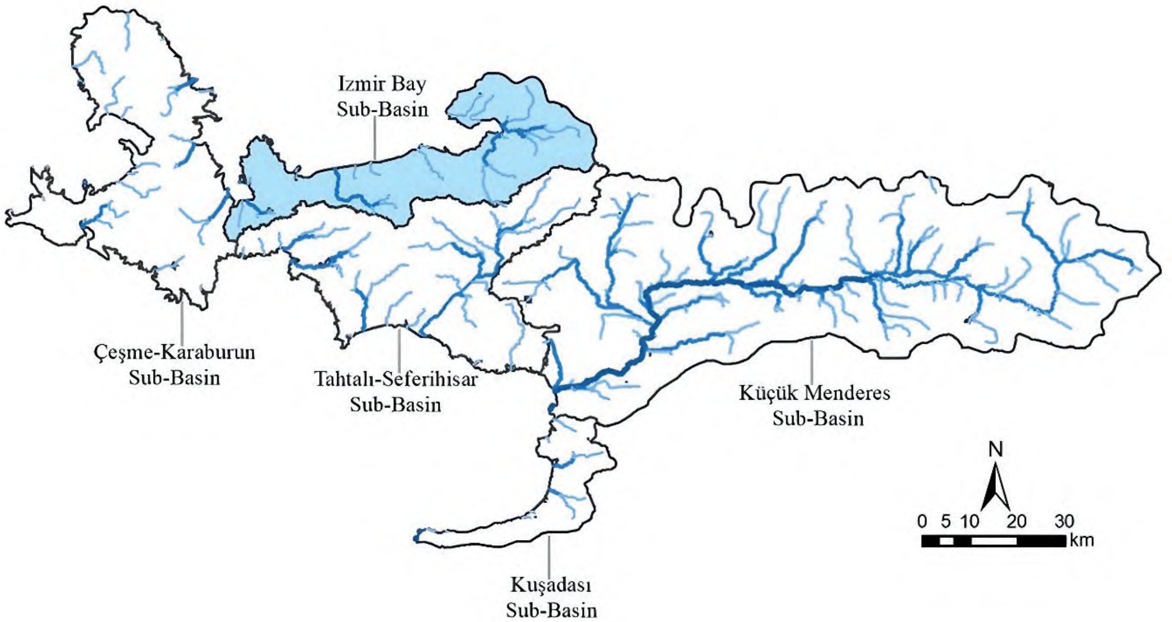

Figure 1. İzmir Bay sub-basin and other sub-basins and stream networks located in the Küçük Menderes basin.
Şekil 1. Küçük Menderes Havzası'nda yer alan İzmir Körfezi alt havzası ve akarsu ağları ile diğer alt havzaları.

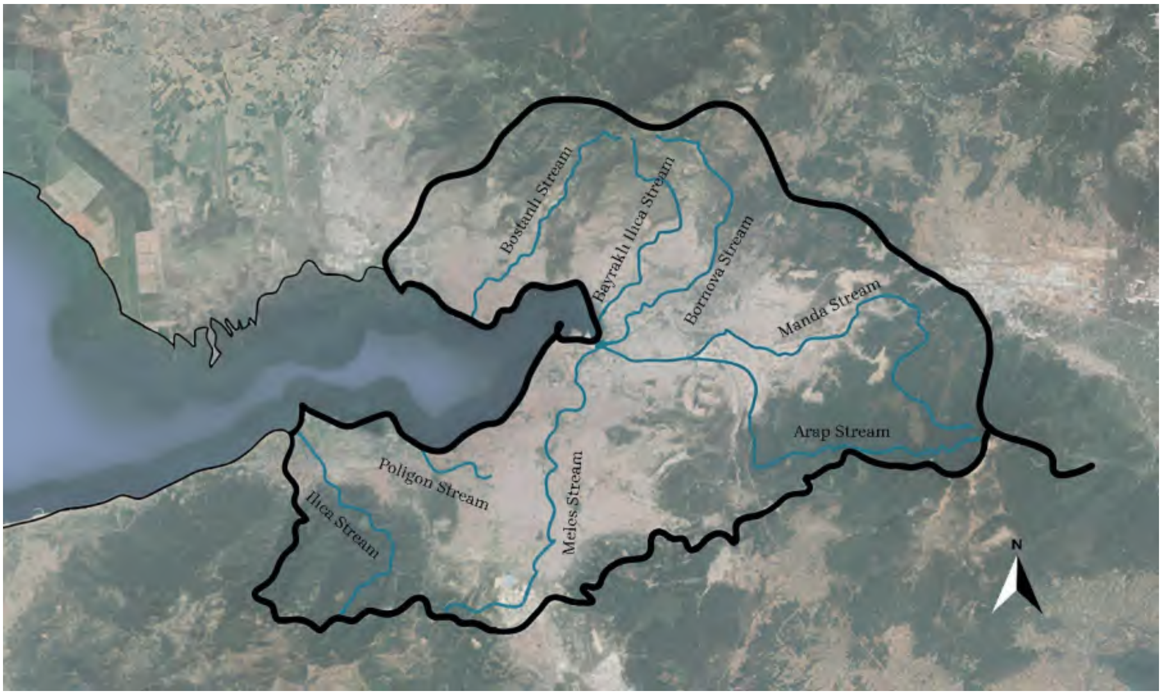

Figure 2. Streams discharging into the inner part of the İzmir Bay sub-basin.

Şekil 2. İzmir Körfezi alt havzasının iç kısmına deşarj olan dereler.

WEAP MODEL AND INPUT DATA

The WEAP model is a comprehensive, scenario-based tool developed by the SEI for water resource assessment, planning and management. It provides a holistic approach to water allocation and sustainability analysis by integrating hydrological processes, water demand, infrastructure operations, and environmental considerations (SEI, 2015). WEAP's user-friendly interface and capabilities allow for effective quick interpretation and visualization of results (Karahan & Elçi, 2023).

WEAP enables users to model both current and future water conditions in a specific region based on key assumptions (Lévite et al., 2003). The model facilitates the exploration of various supply and demand strategies to achieve a balance between environmental sustainability and development needs (Mourad & Alshibabi, 2016). It provides a holistic analysis of water systems by incorporating various hydrological, climatic and socio-economic aspects, such as water demand, supply, streamflow, and groundwater (SEI, 2015). It rapidly generates predictions through scenario-based simulations and presents results across different temporal scales and spatial resolutions. The model helps to evaluate the pressures on existing water systems by integrating external factors such as population growth, climate change, urbanization and policy interventions. By assessing water budget from multiple perspectives and identifying critical areas, WEAP provides researchers, planners, managers and stakeholders with a valuable tool for improving water resource management (Karahan & Elçi, 2023).

Thus, the WEAP model was selected as the most suitable tool for this study due to its flexibility and capability to simulate water supply and demand under various diverse scenarios, as also emphasized by previous studies within the field.

Application of the WEAP Model

There are numerous surface and groundwater resources that supply drinking water to the İzmir Bay sub-basin, some located within the basin and some transferred to the basin from other basins. The reservoirs and groundwater wells taken into account in the WEAP model were identified based on data from both IZSU and the Küçük Menderes Basin (KMB) Master Plan Final Report (2016). Accordingly, the primary surface water resources supplying drinking water to the region include the Tahtalı, Balçova (Cengiz Saran), Ürkmez, Kutlu Aktaş (Alaçatı), Güzelhisar and Gördes dams, shown in Table 1, with Balçova Dam being the only one located within the sub-basin. In terms of groundwater resources, drinking water is extracted from Halkapınar, Pınarbaşı, Buca, and Sarnıç deep-wells within the sub-basin. Additionally, water is also transferred from the Menemen, Çavuşköy, Göksu, and Sarıkız resources in the Gediz Basin to the Küçük Menderes basin to support the drinking water supply for İzmir's central districts, shown in Table 2.

Table 1. Dams and supply amounts from each dam for central districts in the İzmir Bay sub-basin.

Çizelge 1. İzmir Körfezi alt havzası merkez ilçelerine içme suyu sağlayan barajlar ve temin edilen içme suyu miktarları.

Facility Name	Transfer Basin	Purpose of Transfer	Amount of supply for drinking water (hm³/year)
Tahtalı Dam	Küçük Menderes	Drinking water	75.43
Gördes Dam	Gediz	Drinking water + irrigation	44.15
Balçova Dam	Küçük Menderes	Drinking water	5.50
Ürkmez Dam	Küçük Menderes	Drinking water + irrigation	1.22
Güzelhisar Dam	Kuzey Ege	Drinking water + irrigation +industry	9.46
Alaçatı Dam	Küçük Menderes	Drinking water	2.75

Table 2. Drinking water supply amounts from wells for central districts in the İzmir Bay sub-basin.

Çizelge 2. İzmir Körfezi alt havzasındaki merkez ilçeler için kuyulardan temin edilen içme suyu miktarları.

Wells	Basin	Amount of supply for drinking water (hm³/year)
Sarıkız	Gediz	45
Göksu	Gediz	63
Menemen and Çavuşköy	Gediz	25
Halkapınar	Küçük Menderes	45
Pınarbaşı	Küçük Menderes	2
Buca and Sarnıç	Küçük Menderes	1

In WEAP's interface, the schematic view of the calibration model illustrates the study area's water system components, as shown in Figure 3. In this layout, demand sites —where water is used for domestic, agricultural, or industrial purposes— are depicted in red, surface water resources are represented by green triangles, and groundwater wells by green squares. Transmission links, shown as green arrows, illustrate the direction and routing of water flow between supply sources and demand sites (SEI, 2015).

For the hydrological and physical characteristics of the reservoirs, data about available flow, initial storage, storage capacity, net evaporation, and volume-elevation relationships were incorporated into the "current accounts" section of the calibration model. Similarly, for groundwater resources, parameters such as storage capacity, initial storage, natural recharge, and monthly variation values were also included.

In WEAP system, the "current accounts" tool serves as the foundation for developing future scenarios (Yates et al., 2005). These scenarios project potential changes in the system for years beyond the current accounts year. The default scenario, known as the "reference scenario," extends the current account data throughout the entire simulation period and acts as a baseline for comparison with other scenarios where modifications are introduced (Hamlat et al., 2013). In this study, the existing conditions from 2005 were projected forward to the period 2006–2050 without implementing any significant alterations in this scenario. For the Gördes Dam, which started providing drinking water for İzmir in 2019, the activation year was set to that year.

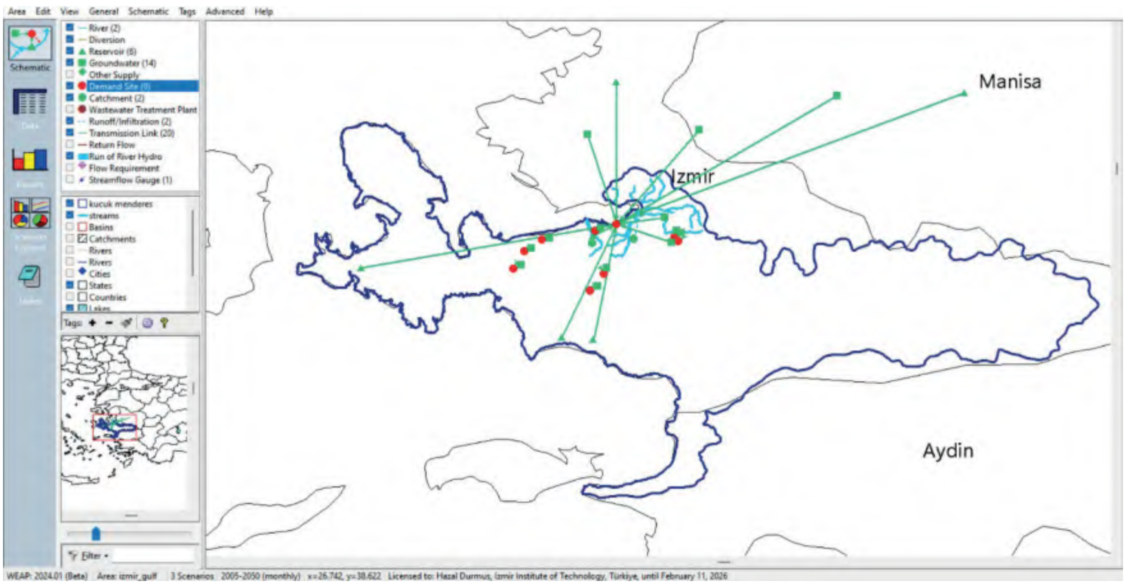

Figure 3. A screenshot of the schematic view of the calibration model from the WEAP interface. The dark blue borders represent the Küçük Menderes basin in which the study area is located, and the light blue lines represent streams within the study area.

Şekil 3. WEAP'in arayüzünden kalibrasyon modelinin şematik görünümünün ekran görüntüsü. Koyu mavi sınırlar çalışma alanının içinde bulunduğu Küçük Menderes havzasını, açık mavi çizgiler ise çalışma alanı içindeki akarsuları temsil etmektedir.

Estimation of projected population and domestic water use

In the WEAP model, in addition to the above-mentioned surface and groundwater information used in the current conditions to calculate the water budget in the sub-basin, population growth projections were also incorporated, which is an important factor affecting the future water demand.

To achieve this, official population records in the central region of İzmir for previous years were obtained from Turkish Statistical Institute, and based on this, three different methods were used to calculate the population projection to the year 2050: arithmetic extrapolation method, geometric extrapolation method and Turkish Bank of Provinces method. Among these, the *Turkish bank of provinces method* was preferred as it projects the largest long-term population and the result was used for all three scenarios in the WEAP simulation.

The Turkish Bank of Provinces method is an alternative method which is widely used for population projections in Türkiye. The projected population *Pn* for a future year is calculated using Equation 1:

$$P_n = P_2\,(1 + K/100)^{(t_2 - t_1)} \tag{1}$$

where P_n is projected population for the target year, P_2 is population recorded in the most recent census year, and K is the average annual growth rate (%). t_2 is the target year (e.g., 2050), while is the most recent census year. The growth rate K is determined by Equation 2:

$$K = \left((P_2/P_1)^{(1/(t_2 - t_1))} - 1\right)100 \tag{2}$$

where P_2 is the population recorded in the most recent census year and P_1 is the population recorded in the earlier census year. t_2 and t_1 are as defined above. The value of K is adjusted according to the following criteria:

$$K = \begin{cases} 3, & if\ K \geq 3 \\ 1, & if\ K \leq 1 \\ K, & if\ 1 < K < 3 \end{cases}$$

According to this method, the population of the İzmir Bay region is projected to reach approximately 3,992,817 people by 2050, and this estimate was used across all three WEAP scenarios.

Also, to estimate the average per capita water consumption in the study area, available data for daily per capita water consumption in İzmir were obtained from the official website of the Turkish Statistical Institute (TurkStat, 2024), given in Table 3, and used as input for the reference scenario.

Estimation of irrigation water needs

In the Mediterranean climate zone, it is expected that the effects of climate change will be strongly felt, and the irrigation water needs of crops grown in the region will inevitably be affected by alterations in precipitation and temperature values (Serbeş et al., 2018).

Table 3. Daily water consumption per person in İzmir (l/day) (TurkStat, 2024).

Çizelge 3. İzmir'de kişi başı günlük su tüketim değeri (l/gün).

	2012	2014	2016	2018	2020	2022
Daily water consumption per person in İzmir (l/day)	223	180	173	208	221	210

In the study, the corresponding irrigation water demand based on agricultural irrigation areas and crop patterns in the İzmir Bay sub-basin represents an important factor when estimating the water budget. Therefore, in order to calculate the irrigation water needs in the region, irrigation areas and crop patterns in the İzmir Bay sub-basin were determined based on the KMB Master Plan Final Report. Agricultural crops grown in the sub-basin include cereals, citrus, corn, fruit, greenhouse crops, olive, ornamental plants, tomato, vegetables and vineyard, which were determined by identifying the agricultural areas in the central districts included in the sub-basin. Accordingly, there are five public irrigation (PI) systems and three special provincial administration (SPAI) irrigation systems that are located in the İzmir Bay region, which are presented in Table 4.

Potential crop evapotranspiration, which is essential for calculating net irrigation water requirements, was estimated using the Blaney-Criddle method (Acatay, 1996; Blaney & Criddle, 1950). This method was chosen due to its ability to perform calculations with minimal input data (Serbeş et al., 2018). The relevant equations are given below in Equations 3–6:

$$U\,(mm/month) = fk \tag{3}$$

$$f = (1.8T + 32)p/100 \tag{4}$$

$$k(mm/month) = k_c k_t (25.4) \tag{5}$$

$$k_t = 0.0173(1.8T + 32) - 0.314 \tag{6}$$

where U is the potential crop evapotranspiration, expressed in millimeters per month; f is the monthly water use factor, k is the monthly water use coefficient. T is the mean monthly air temperature in degrees Celsius, and p is the annual percentage of daytime hours occurring in a given month. K_t is the climate factor, while K_c is the crop development coefficient (Serbeş et al., 2018). The constant 25.4 in the equation is due to the conversion between inches and millimeters. The coefficients 1.8 and 32 are due to the conversion between Fahrenheit and Centigrade temperature units (Koç & Güner, 2005).

Table 4. Spatial distribution of irrigation and crop types in the İzmir Bay sub-basin (ha).

Çizelge 4. İzmir Körfezi alt havzasındaki sulamaların ve ürün türlerinin mekansal dağılımı (ha).

Irrigation's Name	Area	Crop type								
		Cereals	Citrus	Corn	Fruit	Greenhouse	Olive	Tomato	Vegetable	Vineyards
Public Irrigation (PI)										
Kaynakça GW	693	69.3	-	-	304.9	-	103.95	103.95	110.9	-
Kaynakça SW	156.89	15.7	-	-	-	-	141.2	-	15.7	-
Güzelbahçe	199.43	-	39.9	-	-	45.9	83.8	-	29.9	-
Balçova	125	-	10.87	-	11.25	5	-	-	-	-
Yelki	279.92	-	140	-	-	56	-	-	84	-
Special Provincial Administration Irrigation (SPAI)										
Çatalca Şandidere	128.14	12.8	10.25	7.7	-	1.3	10.25	-	63.35	20.5
Yeniköy	280	22.4	-	-	-	2.8	22.4	-	30.8	201.6
Balabandere Bademler 9 Eylül	133.26	-	40	-	46.6	6.65	-	26.65	42.6	-

The values for each crop were entered into the WEAP program after calculating their monthly variation in irrigation areas. Accordingly, the agricultural crop patterns in the report were assumed and estimated crop water need calculations were used in the WEAP model under the current conditions. Each of the irrigation areas was taken into account as a demand site, and the priority of each demand site was equally set to 1, which is the highest priority.

SIMULATIONS OF THE SCENARIOS

In the study, temperature, precipitation, streamflow rate, and water consumption rate were selected as key climatic, hydrological, and demand-related parameters for the simulated scenarios in the WEAP model. In the reference scenario, the average temperature, precipitation, and streamflow rate values measured for the İzmir central region, as documented in the KMB Master Plan Final Report (MFWA, 2016a), were utilized. Also, to determine the average per capita water consumption value in the sub-basin, the average daily per capita water consumption data for the previously available years were obtained from TurkStat, and used as a basis in the reference scenario. The reference scenario provides a baseline for the other scenarios.

In order to construct optimistic and pessimistic scenarios, climate projection data provided in the Impact of Climate Change on Water Resources Project – Appendix for the Küçük Menderes Basin (MFWA, 2016b) were taken as the primary reference. This report includes long-term projections for key climatic and hydrological variables such as temperature, total precipitation, and streamflow under different climate change models. In the optimistic scenario, the simulation was based on the most favorable projections, such as moderate temperature rise, and increases in total precipitation. Conversely, the pessimistic scenario incorporated the most adverse projections, which reflect significant decreases in streamflow, pronounced temperature increases, and substantial decreases in total precipitation. These assumptions were incorporated into the simulations in the WEAP model to assess the future water availability in the sub-basin under contrasting climate change impacts.

According to this, for the optimistic scenario, the MPI-ESM-MR model projection, which predicts the lowest temperature increase, was selected among the available models regarding the projection of temperature. The analysis of the MPI-ESM-MR model for the RCP4.5 scenario in the Küçük Menderes Basin indicates that the annual average temperature is expected to rise by approximately 1.5 °C during the projection period relative to the reference period. Conversely, in the pessimistic scenario, the HADGEM2-ES model projection was chosen, which forecasts the highest temperature increase. The HADGEM2-ES model results for the RCP4.5 scenario suggest that the annual average temperature will increase by approximately 2.8 °C compared to the reference period (MFWA, 2016b).

As for the projection of precipitation, the precipitation projections in the report were analyzed, and the most optimistic and pessimistic model outcomes were utilized for scenario development. In the optimistic scenario, the HADGEM2-ES model projection was adopted, which predicts a 10% increase in total precipitation, as it presents a more favorable outcome compared to other model results. In the pessimistic scenario, a 25% overall decrease in precipitation was assumed based on the collective analysis of all model results (MFWA, 2016b).

Regarding the projection of flow rates, for the optimistic scenario, it was assumed that streamflows would remain at the same levels as those in the reference scenario, which implies no reduction in streamflow. In contrast, the pessimistic scenario was developed based on projections from the MPI-ESM-MR model, which estimates the most severe reductions in streamflow rates. According to this projection, a 20% decrease in streamflow is expected by 2040, followed by a more substantial decrease of approximately 60% in subsequent years (MFWA, 2016b).

Along with these, trends in water consumption were also incorporated into the scenario development. In the optimistic scenario, a 20% reduction in the average water consumption rate was assumed compared to the reference scenario, based on the premise that increased public awareness and the implementation of effective water management practices would enhance water use efficiency. Conversely, in the pessimistic scenario, a 20% increase in average water consumption was assumed, reflecting the possibility of insufficient awareness and poor management strategies, which could exacerbate future water scarcity challenges.

Descriptions of the scenarios simulated in WEAP are summarized in Table 5.

RESULTS AND DISCUSSION

The analysis of future water availability in the İzmir Bay sub-basin reveals significant variations across different scenarios. In 2005, the drinking water potential was estimated at 212.65 hm³. By 2050, the reference scenario projected an increase in demand to 318.25 hm³. The demand for drinking water is expected to rise more moderately, reaching 254.52 hm³ under the optimistic scenario; however, the pessimistic scenario forecasts the highest demand at 381.59 hm³. All results are shown in Table 6.

Table 5. Description of the scenarios simulated in WEAP.
Çizelge 5. WEAP'te simüle edilen senaryoların açıklaması.

Scenarios	Description
Reference Scenario	• Average temperature values were used • Average precipitation values were used • Average streamflow rate values were used • Average daily water consumption per capita information was used based on TurkStat reports
Optimistic Scenario	• Average temperature values were increased by 1.5 °C based on RCP4.5, MPI-ESM-MR model results • Average precipitation values were increased by 10% based on RCP4.5, HadGEM2-ES model results • Average streamflow rate values remained the same • Average daily water consumption per capita was reduced by 20%
Pessimistic Scenario	• Average temperature values were increased by 2.8 °C based on RCP4.5, HadGEM2-ES model results • Average precipitation values were reduced by 25% based on RCP4.5, estimation of all model results • Average streamflow rate values were reduced by 20% until 2040 and by 60% between 2040-2050 based on RCP4.5, MPI-ESM-MR model results • Average daily water consumption per capita was increased by 20%

Regarding delivered supply, the reference scenario results indicate sufficient supply until 2030, after which a shortage begins, and reaches a deficit of 32.4 hm³ by 2050. Under optimistic conditions, supply is expected to meet demand, as shown in Tables 6 and 7. However, in the pessimistic scenario results, delivered supply will not be able to meet demand, and shortages will rise more significantly by 2025 to 2050.

Accordingly, the pessimistic scenario results reveal a dramatic increase in unmet demand, growing from 76.4 hm³ in 2025 to 160.9 hm³ in 2050. The reference scenario results also indicate a steady increase in unmet demand at a slower rate, as shown in the Figure 5. This demonstrates that the region will face water stress, even under current assumptions. However, the optimistic scenario presents the best stable outlook, with water demand and supply remaining balanced.

In terms of irrigation water demand, the annual consumption is projected to increase from 69.45 hm³ in the reference scenario, to 75.35 hm³ under the optimistic scenario and 80.62 hm³ under the pessimistic scenario. Additionally, unmet irrigation water demand, which was 9.12 hm³ at the beginning of the simulation period, is expected to rise to 10.29 hm³ in the reference scenario, 11.15 hm³ in the optimistic scenario, and 14.15 hm³ in the pessimistic scenario. These findings suggest that rising temperatures and shifts in precipitation patterns will lead to a consistent increase in irrigation water demand and result in supply shortages across all future scenarios.

It should be added that the data used in the simulation model, such as planned water allocation values taken from official and institutional reports, suggest specific supply levels; however, real-world constraints such as prolonged droughts and inadequate infrastructure maintenance of facilities often result in lower actual allocations than simulated values. Also, while several planned water sources are mentioned in official reports for the İzmir Bay region, they were excluded from the simulations due to unimplemented status and lack of reliable data. To reduce inconsistencies and uncertainty stemming from varying assumptions across sources, only current and operational data from selected official resources were used. Nevertheless, the study still involves some uncertainties due to differences in data accuracy and consistency across multiple sources. It is important for institutions to share coordinated, up-to-date, and consistent data, allowing researchers access in order to make better evaluations and to improve the accuracy of future predictions.

CONCLUSION AND RECOMMENDATIONS

The demand for water is rising in the modern era due to factors like changing societal and economic needs, and rapid population expansion. Accordingly, water resources are severely strained as a result of excessive water use and pollution caused by urban, agricultural, and industrial activities. These factors, together with the threatening impacts of climate change, have led to a significant increase in water scarcity and inequitable access to water.

Table 6. Annual water demand for drinking water in the İzmir Bay sub-basin (hm³).

Çizelge 6. İzmir Körfezi alt havzasında içme suyu için yıllık talep (hm³).

Scenario	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Reference	254.4	266	278.2	291	304.3	318.25
Pessimistic	305	319	333.6	348.9	364.9	381.59
Optimistic	203.44	212.76	222.51	232.7	243.37	254.52

Table 7. Annual delivered supply for drinking water in the İzmir Bay sub-basin (hm³).

Çizelge 7. İzmir Körfezi Alt havzasında içme suyu için yıllık temin edilen arz (hm³).

Scenario	2025	2030	2035	2040	2045	2050
Reference	254.38	263.88	271.5	277.64	281.97	285.85
Pessimistic	228.63	232.63	236.81	238.2	243.26	220.7
Optimistic	203.44	212.76	222.51	232.7	243.37	254.52

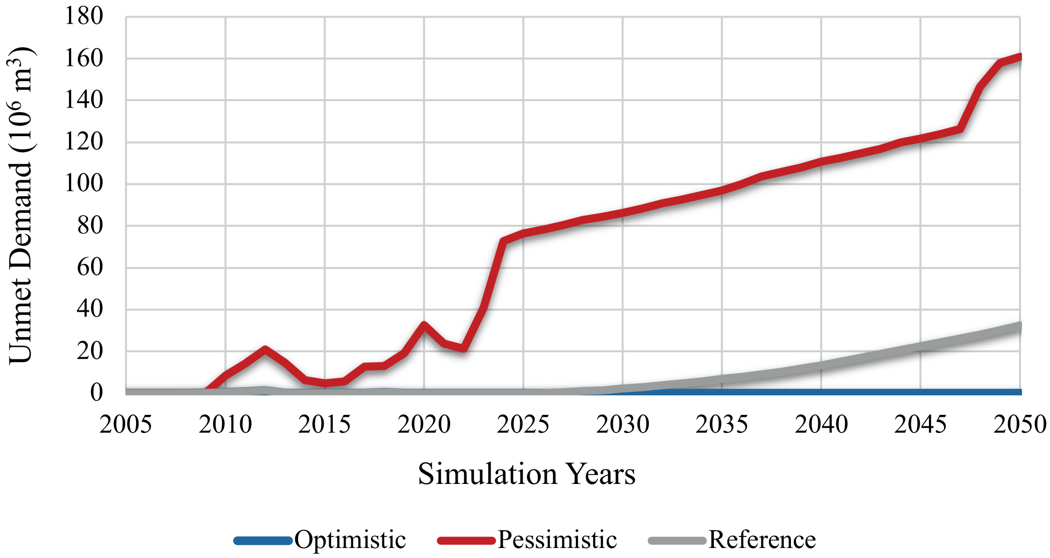

Figure 4. Annual unmet demand (hm³) for drinking water in the İzmir Bay sub-basin under pessimistic, reference and optimistic scenarios throughout the simulation years. The red, grey, and blue lines represent the pessimistic, reference, and optimistic scenario results, respectively.

Şekil 4. Simülasyon yılları boyunca kötümser, referans ve iyimser senaryolar altında İzmir Körfezi alt havzasında yıllık karşılanamayan içme suyu talebi (hm³). Kırmızı, gri ve mavi çizgiler sırasıyla kötümser, referans ve iyimser senaryo sonuçlarını temsil etmektedir.

The İzmir Bay sub-basin, characterized by a semi-arid climate and increasing vulnerability to water scarcity, was assessed using the WEAP model to evaluate its current and projected water potential through the year 2050. Scenario-based simulations reveal that both population growth and the impacts of climate change will drive an increase in domestic and irrigation water demand, thereby exacerbating water deficits throughout the sub-basin. Even under the reference scenario, total water demand for Izmir Bay sub-basin is projected to reach 318.25 hm³ by 2050, indicating an intensification of existing challenges in the near future. In the pessimistic scenario, demand is expected to rise further to 381.59 hm³, with unmet demand reaching 160.9 hm³, highlighting the severity of future supply-demand imbalances if no action is taken.

In terms of irrigation water demand, the optimistic scenario shows an 8.5% increase compared to the reference scenario, while the pessimistic scenario indicates a 16.1% rise. Unmet irrigation water demand is also projected to grow by 12.8% in the reference scenario, 22.2% in the optimistic scenario, and 55.1% in the pessimistic scenario by 2050. These results suggest that the rise in temperatures and changes in precipitation will increase irrigation water demand under all projected conditions.

While alterations in temperature and precipitation patterns are already affecting water availability, several recommendations can be considered to enhance the resilience and sustainability of water resources and to deal with long-term consequences of climate change. Future sustainable irrigation systems must use water resources more wisely. Implementing water-efficient agricultural practices, such as drip irrigation, drought-resistant crop selection, and water reuse strategies, will significantly reduce irrigation water demand. Also, improving the efficiency of existing water resources through maintenance and repair of the existing facilities, and minimization of leakages in urban water distribution systems, are necessary to ensure long-term sustainability. Along with these, protection of natural resources from pollution, controlling and preventing the excessive and illegal use of groundwater, as well as creating new alternative resources, are essential for environmental sustainability.

Moreover, a key challenge in water resource management is the lack of effective regulatory measures, in terms of reducing water use and acting responsibly. Raising public awareness through educational support and sanctions about water conservation are essential for improving responsible water use. For instance, participatory workshops involving local communities, key stakeholders, and farmers could facilitate the adoption of climate-resilient strategies and sustainable water management practices. Integrating local knowledge into policy frameworks is also useful for addressing both short and long-term climate impacts.

Overall, sustainable water management necessitates proactive strategies and effective governance. The formulation of policies aimed at improving water efficiency and minimizing losses requires coordinated efforts between local and central governmental bodies who are responsible for the regulation, management, and supervision of water resources. However, the lack of this integration between authorities, organizations, and policies may cause further complexity and drawbacks. To address these challenges, more comprehensive and collaborative approaches must be implemented. Additionally, climate adaptation strategies must be incorporated into all levels of legal and legislative frameworks to ensure long-term resilience and sustainability.

Ultimately, achieving equitable, adequate and sustainable water distribution significantly depends on well-coordinated management and planning. The optimistic scenario results in supply and demand remaining balanced, indicating the potential for maintaining a stable water supply through well-managed interventions. Therefore, it is necessary for policymakers to implement comprehensive strategies that prioritize water efficiency, conservation of resources, and adaptive management to safeguard the region's water in the face of growing population and climate change effects.

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YAYIN AMAÇLARI VE KURALLARI, YAYINA KABUL İLKELERİ

AMAÇ ve KAPSAM:

JEOLOJİ MÜHENDİSLİĞİ DERGİSİ

- İnsan ile Yerküre arasındaki etkileşimlere ilişkin bilgi ve deneyimleri doğal çevreyi de gözeterek daha güvenli ve sağlıklı bir yaşam ortamı sağlamak amacı ile insanlığın hizmetine sunmayı hedefleyen Jeoloji Mühendisliği mesleğinin, günlük yaşamdaki yerini ve önemini daha etkin bir şekilde yansıtmak,
- Bu alanda ulusal ve uluslararası gelişmeleri Jeoloji Mühendislerinin bilgisine sunmak,
- Konu ile doğrudan veya dolaylı etkinliklerde bulunan bilim insanları, araştırmacılar, mühendisler ve diğer uygulayıcılar arasındaki bilgi ve deneyim paylaşımını güçlendirecek ve hızlandıracak, kolay erişilebilen, geniş katılımlı bir tartışma ortamı sağlamak ve bunları yayma olanağı yaratmak,
- Uluslararası Sürdürülebilir Kalkınma Hedefleri doğrultusunda, doğal kaynakların etkili yönetimi, mühendislik yapıları, mekansal planlamalar, insan ve doğayı yeryüzü dinamiklerini gözeterek, jeolojik tehlikeler göz önünde bulundurularak dirençli ortamların tasarımına katkıda bulunmak ve Jeoloji Mühendisliğine ilişkin diğer sorunların daha etkin bir şekilde çözüme kavuşturulması ve geliştirilmesini sağlamak,
- Disiplinler arası araştırmaların ve birlikte çalışabilirlik ilkelerinin geliştirilmesine katkıda bulunma,

amaçlarına sahiptir.

JEOLOJİ MÜHENDİSLİĞİ DERGİSİ, mühendislik jeolojisi, jeoteknik, su kaynakları yönetimi ve hidrojeoloji, çevre jeolojisi ve atık yönetimi, jeotermal, sondaj tekniği ve uygulamaları, doğal olası tehlikeler, doğa kaynaklı afetler ve afet yönetimi gibi uygulamalı jeoloji mühendisliği hizmetleri konularının yanı sıra, uygulamaya yönelik yerbilim verilerinin de içinde bulunduğu inşaat, maden, jeofizik, petrol, çevre ve şehir bölge planlama gibi disiplinler arası ulusal ve uluslararası araştırmaların yayımlandığı bir dergidir.

Bu kapsamda;

- Mühendislik yapıları için uygun yer seçimi araştırmaları ve arazi kullanım planlamaları,
- Jeoteknik saha araştırmaları, sondaj çalışmaları, arazi ve laboratuvar deneyleri,
- Jeoteknik çalışmalarda kullanılan jeofizik yöntemler,
- Kaya ve zeminlerin jeomekanik özellikleri,
- Şev duraylılığı değerlendirmeleri ve izleme teknikleri,
- İnsan ve doğayı olumsuz etkileyen dinamik jeolojik süreçlere dirençli mekansal planlama çalışmaları,
- Coğrafi Bilgi Sistemleri ve Uzaktan Algılama teknolojilerinin jeoloji mühendisliği alanında uygulamaları,
- Doğal olası tehlike ve risk (Deprem, sıvılaşma, heyelan, obruk, tıbbi jeoloji, taşkın, çığ vb.) değerlendirmeleri,
- Doğa kaynaklı afetler ve afet yönetimi çalışmaları,
- Çevre jeolojisi araştırmaları, atık yönetimi ve yer seçimi çalışmaları,
- Yüzey ve yeraltı su kaynaklarının yönetimi, hidrojeolojik sorunlar ve çözümlere yönelik yaklaşımlar,
- Jeolojik kaynakların yönetimi uygulamaları, sorunları, çözüm önerileri ve ekonomik açıdan değerlendirilmesi,
- Jeotermal, maden ve mineral kaynaklarının araştırma ve geliştirilmesi, yeraltı jeolojisi modelleme çalışmaları,
- Kirleticiler ve ekosisteme etkileri,
- Doğal yapı malzemeleri ve zemin iyileştirme çalışmaları,
- Tarihi yapıların ve jeolojik anıtların korunmasında mühendislik jeolojisi,
- Kaynak arama ve üretim süreçlerindeki sondaj uygulamaları, sondaj teknolojilerindeki gelişmeler,
- Yapı üretim ve denetim süreçlerinde jeoloji mühendisliği alanına giren konulardaki araştırma, geliştirme ve proje çalışmaları,
- Jeoloji Mühendisliği eğitimi ve eğitimin geliştirilmesi,

konuları öncelikli olmak üzere, yukarıdaki konularla ilişkili tüm kuramsal ve uygulamalı çalışmaları kapsayan araştırmalar Jeoloji Mühendisliği Dergisinde yayımlanır. Çalışmanın daha önce yayımlanmamış olması gerekmektedir. Jeoloji Mühendisliği Dergisinde, dört yazı türü yayımlanmaktadır:

1- **ARAŞTIRMA MAKALESİ (Research Article):** Özgün bir çalışmanın sunulduğu yazıdır. Kuramsal temel, yeterli miktar ve nitelikte veriye dayalı bulgu ve sonuçların ayrıntılarıyla değerlendirildiği bölümleri içermelidir. Yazının toplam uzunluğu 9000 sözcük eşdeğerini (15 JMD sayfası) aşmamalıdır. Makale, alanında uzman en az iki hakem tarafından incelendikten sonra yayımlanır.

2- **DERLEME (Review):** Editörün daveti üzerine veya bilgisi dahilinde hazırlanan, Jeoloji Mühendisliği`nin herhangi bir alanında halen kullanılmakta olan teknik, yöntem ve yaklaşımları günümüz teknolojik gelişmeleri ve kendi deneyimleri ışığında inceleyen, bu açıdan öneriler getiren ve geliştiren yazıdır. Yazı uzunluğu konuya bağlı olarak değişebilir. Yayın Kurulu incelemesi zorunluluğu yoktur.

3- **TEKNİK NOT (Technical Note):** Teknik not makalesi, önceki yayınlara kıyasla gerçekten yeni olan bir teknik, ekipman, araştırma yöntemi veya bir değerlendirme yöntemini kapsayan çalışmalardır. Makalede değerlendirme veya ölçüm yöntemlerinin, nasıl doğrulandığı belirtilmelidir. Bir teknik not 4000 kelimeden uzun olmamalıdır (6 JMD sayfası). Makaleler en az iki yayın kurulu üyesi tarafından incelenecektir.

4- **DÜZELTME (Erratum):** Makalenin son düzenleme sırasında yazarlar veya yayın kurulu tarafından yanlışlıkla oluşturulan yayınlanmış bir makaledeki hataları düzeltmek için bir hata bildirimi yayınlanır. JMD, yayınlanan makalenin yazarları veya okuyucular tarafından hatalara karşı uyarılabilir. Yazarlar yayın kurulunu uyardıysa, mümkün olan en kısa sürede bir düzeltme (erratum) yayınlanır. Bir okuyucu yayın kurulunu uyardıysa, bir yazım hatası bildiriminin uygun olup olmadığını görmek için yazarla iletişime geçilir. Okuyucular, Editör ile iletişime geçebilirler. Editöre Mektup alınmışsa ve yazım düzeltmesi gerekliyse, orijinal makalenin yazarlarından, yayınlanan Editöre Mektup'a yanıt vermeleri ve düzeltme yazısı yazmaları istenir.

ETİK İLKELER VE YAYIN POLİTİKASI

1. Etik İlkeler ve Yayın Politikası

Jeoloji Mühendisliği Dergisi (JMD) yayıncı ve kullanıcıları (Editör ve teknik editör, yazarlar, hakemler, okuyucular vb.) Yayın Etiği Komitesi (Committee on Publication Ethics-COPE, https://publicationethics.org/) tarafından belirlenen etik kurallar ve sorumluluklara uyar.

Jeoloji Mühendisliği Dergisi hakemli bir dergidir. Basılı ve elektronik ortamda çevrimiçi yayın yapmakta olup, açık erişim sistemine sahiptir. Dergi sayıları Aralık ve Haziran aylarında yılda iki kez yayınlanır. Yayın süreçlerinde, bilimsel yöntemle özgürce ve yansız biçimde üretilen bilginin paylaşılması gözetilir. Makale değerlendirme sürecinde kör hakemlik sistemi uygulanır. JMD'nin 1977 yılından itibaren yayınlanan tüm sayıları gerek yayıncı kuruluş olan TMMOB Jeoloji Mühendisleri Odası (JMO) tarafından basılı ve elektronik versiyonları, TUBİTAK ULAKBİM- DergiPark tarafından ise elektronik versiyonları arşivlenmektedir.

1.1 Etik İlkeler

Editörlerin Etik Görev ve Sorumlulukları

Jeoloji Mühendisliği Dergisi'nde görev alan Editörler, Yayın Etiği Komitesi (Committee on Publication Ethics -COPE) tarafından " Code of Conduct and Best Practice Guidelines for Journal Editors" başlığı altında yayınlanan kılavuz kapsamında hazırlanan etik görev ve sorumluluklara sahiptir.

Editörler, derginin gelişimi ve yayınlanan çalışmaların kalitesini geliştirmeye yönelik süreçleri takip etmekle sorumludurlar.

JMD'ne sunulan makale ilk olarak, Editörler tarafından dergi amaç ve kapsamına uygunluğu açısından gözden geçirilir. Gönderilen makale, derginin amaç ve kapsamına uymuyorsa en geç 15 gün içerisinde reddedilir ve yazara bilgi verilir. Amaç ve kapsamı uygun bulunan makale, yapılan hakem değerlendirmesi öncesi yazım kuralları, dil ve anlatım ile çalışmanın planlanması açısından incelenir. Bu konularda eksiklikleri bulunan makalelerin yazar tarafından düzeltilmesi istenir.

Editörler, makalelerin tüm bölüm içeriklerini inceleyip, uygun bulduğunda makaleler hakem değerlendirmesine alınır. Ancak, herhangi bir nedenle hakem değerlendirmesine uygun bulunmayan makaleler, editörün değerlendirme raporuyla birlikte reddedilir. Yazara en geç 15 gün içerisinde bilgi verilir.

Hakem değerlendirmesinde makaleler, editör tarafından içerik ve uzmanlık alanlarına göre dergi hakem havuzundan ve/veya havuz dışından olmak üzere, en az üç hakeme gönderilir. Makale hakemlerinin belirlenmesinde, çıkar çatışması/çakışması hususlarına özen gösterilir.

Hakem görüşleri doğrultusunda, düzeltilmesi istenen makalelerin düzeltilmiş kopyası, geçerli bir neden olmaksızın yazarlar tarafından 30 gün içerisinde tekrar editöre gönderilmediği taktirde, editörün makaleyi reddetme hakkı vardır. Yeniden düzenleme sonrası, düzeltilmiş makale editör tarafından gerekirse yeniden hakem değerlendirmesine gönderilir veya editör tarafından doğrudan kabul veya reddedilir.

Değerlendirme sonucu, hakemlerden gelen görüşler, editör tarafından en geç 15 gün içerisinde incelenir. İnceleme sonucunda, editör makaleye ilişkin nihai kararını vererek yazara iletir. Ret kararı verilen makaleler arşivlenir.

Editörler; olası suistimal ve görevi kötüye kullanma işlemlerine karşı önlem almakla yükümlüdür. Bu duruma yönelik şikayetlerin belirlenmesi ve değerlendirilmesi konusunda titiz ve nesnel bir soruşturma yapmanın yanı sıra, konuyla ilgili bulguların paylaşılması, editörün sorumlulukları arasında yer almaktadır. Suistimal şüphesi veya tartışmalı yazarlık durumlarında COPE akış şemaları (https://publicationethics.org/resources/translated-resources/turkish-all-flowcharts) dikkate alınarak gerekli aşamalar izlenir.

Editörler; yazar, hakem veya okuyuculardan gelen şikayetleri dikkatlice inceleyerek aydınlatıcı ve açıklayıcı bir şekilde yanıt vermekle yükümlüdür.

Dergi sahibi, yayıncı ve diğer hiçbir politik ve ticari unsur, editörlerin bağımsız karar almalarını etkilemez.

Editörler; yazar(lar), hakemler ve diğer editörler arasındaki çıkar çatışmalarını göz önünde bulundurarak, çalışmaların yayın sürecinin bağımsız ve tarafsız bir şekilde tamamlamasını garanti eder.

Hakemlerin Etik Görev ve Sorumlulukları

Jeoloji Mühendisliği Dergisi'nde görev alan Hakemler, Yayın Etiği Komitesi (Committee on Publication Ethics -COPE) tarafından "COPE-Ethical Guidelines for Peer Reviewers" başlığı altında yayınlanan kılavuz kapsamında hazırlanan etik görev ve sorumluluklara sahiptir.

- JMD'de tüm bilimsel yayınların objektif değerlendirilmesini sağlamak amacıyla kör hakemlik sistemi uygulanmaktadır. Makaleye hakem atama aşamasında hakem ve yazar(lar) arasında herhangi bir çıkar çatışması/çakışması bulunmamasına özen gösterilmektedir. Bu amaçla hakem ve yazar(lar) arasında bilhassa;
  - o Tez danışmanı/öğrenci ilişkisi olmaması,
  - o Yazar(lar) ve hakem arasında yakın geçmişte (son 2 yıl) ortak araştırma ve yayın yapılmamış olması,
  - o Aynı kurumda görev yapıyor olmaması,
  - o Dergiye sunulan yazıya biçim ya da içerik yönünden katkı yapmamış olması,
  - o Yazar(lar) ve hakem arasında yargıya ya da etik kurullara intikal eden ihtilafların olmaması,
  - o Hakem ve yazar(lar) arasında akrabalık ilişkisinin olmaması,
  - o Hakemin yazar(lar) hakkında kamuoyuna intikal etmiş önyargılarının bulunmaması,

- o Hakem ve yazar(lar) arasında herhangi bir ticari ilişkisinin olmaması,

gibi durumlar dikkate alınır. Yukarıda belirtilen ve dergi editörlüğünün gözünden kaçan durumların olması ihtimaline karşı hakemler editörü uyarır ve gerekli bilgiyi verir.

Ayrıca;

- Hakemler, sadece uzmanlık alanlarına giren makaleleri değerlendirir.
- Hakemler değerlendirmelerini tarafsız, objektif ve gizlilik içinde yapmakla yükümlüdürler.
- Değerlendirmede milliyet, cinsiyet, dini inanç, siyasal düşünce, ticari kaygılar vb. nedenlerle tarafsızlıklarını kaybetmemelidirler.
- Görüş ve önerilerini akademik görgü kuralları içinde, yapıcı ve akademik bir dille yapmaları, kişisel polemik yaratacak üsluptan kaçınmaları gerekmektedir.
- Yayın sürecini sebepsiz uzatacak şekilde değerlendirmelerini geciktirmemeleri gerekir. Hakem değerlendirme süreci için hakemlere verilen süre 30 gündür. Hakemler veya editörden gelen düzeltme önerilerinin yazarlar tarafından 30 gün içerisinde tamamlanması zorunludur. Hakemler makale için düzeltmelerini inceleyerek uygunluğuna karar verebilir veya gerekliyse birden çok defa düzeltme talep edebilir.

Yazarların Etik Görev ve Sorumlulukları

JMD'nde uygulanan yayın süreçleri, bilginin tarafsız ve saygın bir şekilde gelişimine ve dağıtımına temel teşkil etmektedir. Bu doğrultuda uygulanan süreçler, yazarların ve yazarları destekleyen kurumların çalışmalarının kalitesine doğrudan yansımaktadır. Hakemli çalışmalar bilimsel yöntemi somutlaştıran ve destekleyen çalışmalardır. Bu noktada sürecin bütün paydaşlarının (yazarlar, okuyucular ve araştırmacılar, yayıncı, hakemler ve editörler) Yayın Etiği Komitesi-COPE ilkelerine uyması önem taşımaktadır.

JMD'ne değerlendirilmek üzere makale gönderecek yazar(lar), öncelikle DergiPark'a üye olmak zorundadır. Sorumlu yazar çalışmalarını (orijinal makale, derleme, vb.) JMD'ne DergiPark sistemi üzerinden göndermelidir.

Makaleden sorumlu yazarın dergiye yeni makale gönderimi için "iThenticate İntihal Tespit Yazılımı" veya "Turnitin" veya eşdeğeri bir intihal programı kullanarak benzerlik raporunun yanı sıra, imzalanan "Telif Hakkı Devri Formu" ve "Etik Bildirim Formu"nu DergiPark sistemine yüklemesi gerekmektedir. Gönderilen makalenin benzerlik endeksi oranı, referans listesi hariç, % 20`nin altında olmalıdır.

Yazarlar çalışmalarını aynı anda birden fazla derginin başvuru sürecinde bulunduramaz. Her bir başvuru önceki başvurunun tamamlanmasını takiben başlatılabilir. Başka bir dergide yayınlanmış çalışma JMD'ne gönderilemez.

Sorumlu yazar, gönderilen bu makalenin başka bir yerde benzer bir formda yayınlanmadığını, makalenin orijinal olduğunu ve yayınlanmak üzere başka bir yere gönderilmeyeceğini garanti etmelidir.

Yazar(lar)ın gönderdikleri çalışmaların özgün olması beklenmektedir. Yazar(lar)ın başka çalışmalardan yararlanmaları veya başka çalışmaları kullanmaları durumunda eksiksiz ve doğru bir biçimde atıfta bulunmaları ve/veya alıntı yapmaları gerekmektedir.

Yazar(lar)dan değerlendirme süreçleri çerçevesinde makalelerine ilişkin ham veri talep edilebilir; böyle bir durumda yazar(lar) beklenen veri ve bilgileri yayın kuruluna sunmaya hazır olmalıdır.

Yazar(lar), kullanılan verilerin kullanım haklarına, araştırma/analizlerle ilgili gerekli izinlere sahip olduklarını gösteren belgeye sahip olmalıdır.

Makale yazarlarının her biri makaleye önemli bilimsel katkıda bulunmuş olması gerektiğinden her yazarın eşit etik sorumluluk taşıdığı kabul edilir. Yazar(lar)ın yayınlanmış, erken görünüm veya değerlendirme aşamasındaki çalışmasıyla ilgili bir yanlış ya da hatayı fark etmesi durumunda, dergi editörünü veya yayıncıyı bilgilendirme, düzeltme veya geri çekme işlemlerinde editörle iş birliği yapma yükümlülüğü bulunmaktadır.

Değerlendirme aşamasındaki makalesini geri çekme isteğinde bulunan yazar(lar)ın, konuyu içeren ıslak imzalı dilekçeyi dergi e-posta adresi jmd@jmo.org.tr üzerinden yayın kuruluna iletmesi gerekir. Yayın Kurulu, geri çekme dilekçesini inceleyerek en geç 15 gün içerisinde cevap verir. Yayın Kurulu tarafından dilekçesi onaylanmayan bir makalenin yazar(lar)ı, makalelerini başka bir dergiye gönderemezler.

Yayınlanmak üzere gönderilen tüm çalışmaların varsa çıkar çatışması teşkil edebilecek durumları ve ilişkileri açıklanmalıdır.

Değerlendirme süreci başlamış bir çalışmanın yazar sorumluluklarının değiştirilmesi (Yazar ekleme, yazar sırası değiştirme, yazar çıkartma gibi) teklif edilemez.

Değerlendirme sürecinde yazarlar; editör ve hakemlerin görüş, öneri ve eleştirilerine cevap vermekle yükümlüdürler. Yazarlar, hakem görüşlerini dikkate alarak sorulan soruları cevaplamak, görüş ve önerileri değerlendirmek, eleştirilere karşı olumlu ya da olumsuz karşılık vererek bunlara dair kanıtlarını ayrıntılı bir mektupla editöre bildirmek zorundadır. Bu karşı mektupta akademik üslup kullanılmalı, kişisel tartışmalardan kaçınılmalıdır.

1.2 Yayın Politikası

JMO ve/veya JMD yayınlanacak makalelerin telif haklarının alınması için yazarlardan yazılı onay alır. İlgili yazar, dergiye sunulan makalenin yazarı/sahibi olduğunu ve kendisi ve diğer yazar(lar) adına telif hakkını JMO ve/veya JMD'ne devreder. Telif Hakkı Devri Formunun doldurularak, makale sunumu esnasında dergi sistemine yüklenmesi zorunludur.

Sunulan makalenin tüm yazarları, yazının tüm haklarını ve tüm telif haklarını imzalayarak JMO ve/veya JMD'ne devretmelidir. JMO ve/veya JMD'nin, ilgili makalenin tamamını veya bir kısmını dersler/ders notları, raporlar ve ders kitapları/basılı kitaplar gibi gelecekteki eserlerinde herhangi bir ödeme yapmadan kullanma hakkı ve ilgili makalenin kendi kullanımı için kopyasını alma hakkı vardır. JMO ve/veya JMD; ticari amaçlar dışında patent hakları gibi telif hakkı dışındaki tüm haklarını saklı tutar.

JMD sistemindeki tüm kişisel bilgiler bilimsel amaçlarla kullanılmakta olup, üçüncü taraflarla paylaşılmamaktadır.

Editör, Teknik Editör ve Yayın Kurulu üyeleri, yazarların görüşlerinden ve yazı içeriğinden sorumlu değildir. Yazarlar, yazılarındaki etik özgünlük ve olası hatalardan sorumludur. Son okuma (düzeltme okuması) öncesi ve sayfa düzenleme aşamasında oluşabilecek tüm hatalardan yazarlar sorumludurlar. Son okuma sonrası meydana gelen hatalar dergi yetkililerinin sorumluluğundadır.

YAZIM KURALLARI

JEOLOJİ MÜHENDİSLİĞİ DERGİSİ'nin yayın dili Türkçe ve İngilizcedir. Makale hangi dilde hazırlanmışsa Başlık, Öz, Şekil ve Çizelge açıklamalarını takiben diğer dildeki karşılığı yazılmalıdır. Yazarların ana dillerinin Türkçe olmaması ve bu konuda makalenin dergiye sunumundan önce gerekli yardımı alamamaları durumunda, Başlık, Öz, Şekil ve Çizelge başlıklarının Türkçeye çevrilmesinde Editörler gerekli yardımı sağlar. Ana dili İngilizce olmayan yazarlara, yazılarını DergiPark sistemine yüklemeden önce, dil bilgisi ve yazım tarzı açısından, ana dili İngilizce olan bir kişiden katkı almaları özellikle önerilir.

Dergiye yayımlanmak üzere gönderilen makaleler, dergi yazım kurallarına göre hazırlanmalıdır.

Dergi yazım kurallarına göre hazırlanmış MS Office Word şablonunu bilgisayarınıza indirmek için lütfen **tıklayınız**...

Dergiye yayımlanmak üzere gönderilen makaleler, Etik İlkeler ve Yayın Politikası dikkate alınarak hazırlanmış olmalıdır.

Tüm makaleler Jeoloji Mühendisliği Dergisi DergiPark Sistemi üzerinden https://dergipark.org.tr/tr/journal/1669/submission/step/manuscript/new adresindeki "Makale Gönder" menüsü aracılığıyla elektronik ortamda gönderilmelidir.

Bunun için önce DergiPark sistemine üye olmalısınız. Makale Gönderim Aşamasında karşınıza çıkan Etik Beyan formu ve Telif Hakkı Devir formlarının düzenlenip, makale dosyalarıyla birlikte sisteme yüklenmesi gerekmektedir.

Yazılar aşağıda verilen düzen çerçevesinde hazırlanmalıdır:

(a) Başlık (Türkçe ve İngilizce)
(b) Yazarların Ad(lar)ı SOYAD(LAR)I koyu olacak şekilde, adresleri (italik ve küçük harfle) ile sorumlu yazarın e-posta adresi
(c) Öz (Türkçe ve İngilizce)
(d) Anahtar Kelimeler (Türkçe ve İngilizce)
(e) Giriş (amaç, kapsam ve yöntemi)
(f) Ana metin (kullanılan yöntemler, çalışılan malzemeler, tanımlamalar, analizler vd.)
(g) Tartışma ve Sonuçlar veya Sonuçlar
(h) Katkı Belirtme
(i) Kaynaklar

Metinde kullanılan değişik türde başlıklar farklı şekillerde ve tüm başlıklar sayfanın sol kenarında verilmelidir. Ana başlıklar büyük harflerle ve koyu yazılmalıdır. İkinci derece başlıklar alt başlık olarak değerlendirilmeli ve birinci ve ikinci derece alt başlıklar küçük harfle (birinci derece alt başlıklarda her kelimenin ilk harfi büyük) ve koyu, üçüncü derece alt başlıklar ise italik olmalıdır. Başlıkların önüne numara veya harf konulmamalıdır. Yazılar (öz, metin, sponsor, katkı belirtme, kaynaklar, ekler ve şekiller dizini) A4 (29.7 cmX21 cm) boyutundaki sayfaların bir yüzüne, kenarlardan en az 2.5 cm boşluk bırakılarak, 1,5 satır aralığında ve 12 puntoyla (Times New Roman) yazılmalı, ayrıca tüm sayfalara numara verilmelidir.

Başlıklar şu şekilde olmalıdır:

ÖZ

ABSTRACT

GİRİŞ

ANA BAŞLIK

Birinci Derece Alt Başlık

İkinci derece alt başlık

Üçüncü derece alt başlık

SONUÇLAR ve TARTIŞMA

KATKI BELİRTME

ORCID

KAYNAKLAR

Başlık ve Yazarlar

Yazının başlığı, çalışmanın içeriğini anlaşılır şekilde yansıtmalıdır. Eğer yazı Türkçe hazırlanmışsa, Türkçe başlığı (koyu ve kelimelerin ilk harfleri büyük harf olacak şekilde) İngilizce başlık (italik ve kelimelerin ilk harfleri büyük olacak şekilde) izlemelidir. İngilizce hazırlanmış yazılarda ise, İngilizce başlık Türkçe başlıktan önce ve yukarıda belirtilen yazım kurallarına göre verilmelidir.

Makaledeki yazarlar, eğer henüz yoksa http://orcid.org web adresinden edinecekleri ORCID (ORCID, Open Researcher ve Contributor ID'nin kısaltmasıdır. ORCID, Uluslararası Standart Ad Tanımlayıcı (ISNI) olarak da bilinen ISO Standardı (ISO 27729) ile uyumlu 16 haneli bir numaralı URL›dir.) bilgilerini de makale ile birlikte sunmalıdır.

Yazarlara ilişkin bilgi ise aşağıdaki örneklere uygun olarak verilmelidir.

Tolga ÇAN

Çukurova Üniversitesi, Mühendislik Fakültesi, Jeoloji Mühendisliği Bölümü, 01250 Adana

e-posta: tolgacan@cu.edu.tr

ORCID Numarası: 0000-0001-9940-2832

ÖZ

Çalışma hakkında bilgi verici bir içerikle (çalışmanın amacı, elde edilen başlıca sonuçlar) ve 200 kelimeyi aşmayacak şekilde hazırlanmalıdır. Özde kaynaklara atıfta bulunulmamalıdır. Makalelerde hem Türkçe hem de İngilizce Öz bulunmalıdır. Türkçe yazılarda ilk önce Öz, daha sonra "Abstract" (İtalik), İngilizce yazılarda ise önce Abstract daha sonra Türkçe Öz (italik) olacak şekilde hazırlanmalıdır.

Anahtar Kelimeler

Öz ve Absract'ın altında sırasıyla Türkçe ve İngilizce olarak en az 3-6 kelimeyi aşmayacak şekilde ve yazının konusunu yansıtan anahtar kelimeler verilmelidir. Anahtar kelimeler, alfabetik sırayla, birinci anahtar kelimenin ilk harfi büyük, diğerleri ise küçük harflerle yazılmalı ve aralarına virgül konmalıdır. Teknik Not türü yazılarda anahtar kelimelerin verilmesine gerek yoktur.

KATKI BELİRTME

Katkı belirtme, kısa olmalı ve teşekkür edilecek olanlar çalışmaya en önemli katkıyı sağlayan kişilerin ve/veya kuruluşların adlarıyla sınırlandırılmalıdır. Teşekkür edilecek kişilerin açık adları ünvanları belirtilmeksizin verilmeli, ayrıca bu kişilerin görevli oldukları kurum ve kuruluşların adları da eklenmelidir.

Hibe, proje fon desteği vb. teşekkürleri bu başlık altında ayrı bir paragraf olarak belirtilmelidir. Finansman sağlayan kuruluşların isimleri tam olarak yazılmalıdır.

Araştırma sırasında yardım sağlayan kişiler burada listelenmelidir (örneğin, İngilizce tercüme desteği sağlamak, yazım yardımı veya makalenin Türkçe ve İngilizce düzeltmesini yapmak vb.).

DEĞİNİLECEK BELGELER

Metin İçinde Atıfların Yazılması

A. Yayında tek yazar varsa

Parantez içinde yazılması gerekiyorsa: (Yazar1, Tarih) Ör: (Sönmez, 1996)

Metin içinde yazılması gerekiyorsa: Yazar1 (Tarih) Ör: Sönmez (1996)

B. Yayında 2 yazar varsa

Parantez içinde yazılması gerekiyorsa: (Yazar1 ve Yazar2, Tarih) Ör: (Merriman ve Frey, 1999)

Metin içinde yazılması gerekiyorsa: Yazar1 ve Yazar2 (Tarih) Ör: Merriman ve Frey (1999)

C. Yayında 2'den fazla yazar varsa

Parantez içinde yazılması gerekiyorsa: (Yazar1 vd., 1987) Ör: (Pettijohn vd., 1987)

Metin içinde yazılması gerekiyorsa: Yazar1 vd. (1987) Ör: Pettijohn vd. (1987)

D. Arka arkaya birden fazla atıfta bulunulacaksa

Parantez içinde yazılması gerekiyorsa: (Merriman ve Frey, 1999; Pettijohn vd., 1987; Sönmez, 1996)

Metin içinde yazılması gerekiyorsa: Merriman ve Frey (1999), Pettijohn vd. (1987), Sönmez (1996)

. Aynı yazarların aynı yıl içinde birden fazla yayınına atıfta bulunulduysa

Bu durumda Kaynaklar bölümünde makalelerin tarihlerinden sonra a, b, c gibi harfler verilir, metin içindeki atıflarda da tarihlerden sonraki harfler kullanılır.

Kaynakçada:

Ahmetoğlu, A. ve Hüsnüoğlu, H. (2022a). Makale Adı 1. Süreli yayının/derginin adı (kısaltılmamış), Cilt No(Sayı No), sayfa numaraları. Varsa DOI bilgisi

Ahmetoğlu, A. ve Hüsnüoğlu, H. (2022b). Makale Adı 2. Süreli yayının/derginin adı (kısaltılmamış), Cilt No(Sayı No), sayfa numaraları. Varsa DOI bilgisi

Metin içindeki atıflarda:

Parantez içinde yazılması gerekiyorsa: (Ahmetoğlu ve Hüsnüoğlu, 2022a)

Metin içinde yazılması gerekiyorsa: Ahmetoğlu ve Hüsnüoğlu (2022a)

Kaynaklar Bölümü

Aşağıdaki örnekler ile kesinlikle uyumlu olmalıdır

- JMD'de Türkçe yayınlanacak makalelerde: Kaynak çok isimli bir çalışma ise: Son isimden önce "ve" gelmelidir eğer kaynak İngilizce ise "&" kullanılmalıdır.
- Editörün belirtilmesi gereken çalışmalarda: Tek isim ise (Ed.) çoklu editör ise: Son isimden sonra (Ed.ler) eğer kaynak İngilizce ise (Eds.) yazılmalıdır.

A. Süreli yayınlar:

A.1. Süreli yayınların gösterilmesi:

Yazar ad(lar)ı, (Tarih). Makalenin başlığı. Süreli yayının/derginin adı (kısaltılmamış), Cilt No(Sayı No), sayfa numaraları. Varsa DOI bilgisi

Hoek, E. & David, M. (1990). Estimating Mohr – Coulomb friction and cohesion values from Hoek – Brown failure criterion. International Journal of Rock Mechanics, 27(3), 220-229. https://doi.org/10.1016/0148-9062(90)94333-O

A.2. Özel durumlar:

A.2.1. Eğer makale serbest erişimli bir internet sayfasından alındıysa:

Ketin, İ. (1949). Son on yılda Türkiye'de vukua gelen büyük depremlerin tektonik ve mekanik neticeleri hakkında. Türkiye Jeoloji Bülteni, 2(1), 1-13. https://dergipark.org.tr/tr/pub/tjb/issue/50279/650044

A.2.2. Eğer makalenin makale numarası varsa:

Açlan, M., Oyan, V. & Köse, O. (2020). Petrogenesis and the evolution of Pliocene Timar basalts in the east of Lake Van, Eastern Anatolia, Turkey: A consequence of the partial melting of a metasomatized spinel–rich lithospheric mantle source. Journal of African Earth Sciences, 168, Article 103844. https://doi.org/10.1016/j.jafrearsci.2020.103844

B. Bildiriler:

Yazar ad(lar)ı, (Tarih). Bildirinin başlığı. Editör(ler), Sempozyum veya Kongrenin Adı, (bildirinin sayfa aralığı). Yayınevi. Varsa DOI bilgisi veya internet erişim bilgisi

Şanlıyüksel Yücel, D., İleri, B. (2019). Characterization of weak, strafied and clay bearing rock masses. H. Sözbilir, Ç. Özkaymak, B. Uzel, Ö. Sümer, M. Softa, Ç. Tepe, S. Eski (Ed.ler), 72. Türkiye Jeoloji Kurultayı Bildiri Özleri ve Tam Metin Bildiriler Kitabı, (s.63-64). Jeoloji Mühendisleri Odası Yayınları. https://www.jmo.org.tr/resimler/ekler/174e0f6fa731893_ek.pdf

C. Kitaplar:

C.1. Kitapların gösterilmesi:

Yazar ad(lar)ı, (Tarih). Kitabın Adı (ilk harfleri Büyük). Yayınevi. Varsa DOI bilgisi veya internet erişim bilgisi

Pettijohn, F. J., Potter, P. E. & Siever, R. (1987). Sand and Sandstones (2nd ed.). Springer-Verlag New York. https://www.doi.org/10.1007/978-1-4612-1066-5

Ketin, İ. (2016). Genel Jeoloji, Yerbilimlerine Giriş (9. Baskı). İTÜ Vakfı Yayınları.

C.2. Çeviri Kitapların Gösterilmesi:

Yazar ad(lar)ı, (Tarih). Kitabın Çeviri Adı (Çevirenlerin adları). Yayınevi. (Orijinal yayın tarihi). Varsa DOI bilgisi veya internet erişim bilgisi

Komatina, M. M. (2011). Tıbbi Jeoloji: Jeolojik Ortamların İnsan Sağlığı Üzerindeki Etkileri (Çev: Y. Örgün ve D. Bayrak). TMMOB Jeoloji Mühendisleri Odası (Orijinal yayın tarihi: 2001).

D. Kitapta Bölüm ise:

Yazar ad(lar)ı, (Tarih). Bölüm Adı. Editör(ler) Kitap adı (Bölümün sayfa aralığı). Yayınevi.

Merriman, R. J. & Frey, M. (1999). Patterns of very low-grade metamorphism in metapelitic rocks. In M. Frey & D. Robinson (Eds.), Low Grade Metamorphism, (pp. 61-107). Blackwell Sciences Ltd.

E. Raporlar ve Tezler:

E.1. Raporlar:

Yazar ad(lar)ı, Tarih. Raporun başlığı (Varsa rapor no). Kurum adı (Yayımlanma durumu).

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Sönmez, H. (1996). TKİ ELİ Soma Linyitleri açık işletmelerinde eklemli kaya kütlesi içindeki şevlerin duraylılığının değerlendirilmesi [Yayımlanmamış Yüksek Lisans Tezi]. Hacettepe Üniversitesi Fen Bilimleri Enstitüsü.

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H. Kaynak olarak kullanılan haritalar:

Konak, N. ve Ercan, T., 2002. 1/500.000 Türkiye Jeoloji Haritası Van Paftası, (Şenel, M., (Ed.)). Maden Tetkik ve Arama Genel Müdürlüğü Yayınları, Ankara.

Türkçe kaynaklar doğrudan Türkçe olarak verilmeli ve Türkçe karakterlerle yazılmalıdır.

EŞİTLİKLER

Matematiksel sembolleri ve formülleri resim olarak değil, lütfen düzenlenebilir metin olarak gönderin. Denklemler için denklem düzenleyicisini veya MathType'ı kullanın. Eşitliklerde, yaygın olarak kullanılan uluslararası simgelere yer verilmesine özen gösterilmelidir. Her eşitliğe sırayla numara verilmeli, numaralar parantez içinde eşitliğin hizasında ve sayfanın sağ kenarında belirtilmelidir. Prensip olarak, değişkenler italik olarak sunulmalıdır. "e" nin kuvvetleri "(exp)" ile gösterilmelidir. Eşitliklerde kullanılabilecek alt ve üst indisler belirgin şekilde ve daha küçük karakterlerle yazılmalıdır (Id, x2 gibi). Eşitliklerdeki sembollerin açıklamaları eşitliğin hemen altındaki ilk paragrafta verilmelidir. Karekök işareti yerine parantezle birlikte üst indis olarak 0.5 kullanılmalıdır (σcmass= σc0.5 gibi). Bölme işareti olarak yatay çizgi yerine "/" simgesi kullanılmalıdır. Çarpma işareti olarak genellikle herhangi bir işaret kullanılmamalı, ancak zorunlu hallerde "*" işareti tercih edilmelidir (y=5 * 10-3 gibi). Kimyasal formüllerde iyonların gösterilmesi amacıyla Ca++ veya CO- - gibi ifadeler yerine Ca+2 ve CO3-2 kullanılmalıdır. Metinde eşitliklere "eşitlikler (1, 2, vb.)" şeklinde atıfta bulunulmalıdır. Eşitlik verildikten sonra ilgili parametreler açıklanmalıdır.

ÇİZELGE VE ŞEKİLLER

Çizelge ve şekiller metin içerisinde yer almalıdır. Çalışmanın sonunda ayrıca verilmemelidir. Çizelge ve şekillerde genel şablonun dışında 10 punto Times New Roman yazı karakteri kullanılır. Paragraf sekmesinde girintiler bölümünde; önce ve sonra alanı 0, satır aralığı tek olmalıdır. Tablo ve şekiller sola dayalı olmalı ve metin kaydırma özelliği kapalı olmalıdır. Çizelge ve şekiller Dergi'nin tek (7.5 cm-genişlik) veya çift (16 cm-genişlik) kolonuna sığacak şekilde düzenlenmelidir.

Çizelgeler

Çizelgeler, başlıklarıyla birlikte, Dergi'nin sayfalarındaki baskı alanını (16 x 22cm) aşmayacak şekilde hazırlanmalı ve birbirini izleyen sıra numaralarıyla verilmelidir. Çizelgelerin üst kısımlarında hem Türkçe hem de İngilizce başlıkları bulunmalıdır. Makalenin Türkçe yazılması halinde İngilizce başlık italik harflerle Türkçe başlığın altında yer almalı, İngilizce makalelerde ise, italik yazılmış Türkçe başlık İngilizce başlıktan sonra verilmelidir. Çizelgeler, "Çizelge 1" vb. şeklinde sunulmalıdır. Metinde çizelgelere Çizelge 1 veya Çizelge 1 ve 2 (eğer birden fazla sayıda çizelgeye atıfta bulunulacaksa) şeklinde değinilmelidir. Çizelgeler içindeki karakterler 10 punto (duruma göre daha küçük) yazılmalıdır. Çizelgelerde düşey çizgiler kullanılmamalı, yatay çizgiler ise sadece çizelgenin alt ve üstünde, ayrıca çizelgedeki başlıklar ile bunların altında listelenen rakamları ayırmak için kullanılmalıdır (Bunun için Dergi'nin önceki sayılarına bakılması önerilir). Çizelgelerde makalenin diğer kısımlarında verilen bilgi veya sonuçların (örneğin grafikler vb.) tekrar verilmemesine özen gösterilmelidir. Çizelgelerle ilgili varsa verilmesi gereken açıklamaları daha küçük karakterlerle çizelgenin altında belirtebilirsiniz.

Şekiller

Çizim, grafik ve fotoğraf gibi tüm şekiller yüksek kalitede basılmış olarak "Şekil" başlığı altında ve metin içinde anıldıkları sırayla numaralandırılarak verilmelidir. Çizim, grafik ve fotoğraf formatlarında aşağıda önerilen kurallar dikkate alınmalıdır.

Kullanılan uygulama ne olursa olsun, elektronik fotoğraf/ grafik sonlandırıldığında, 'farklı kaydet' seçeneğini kullanarak görüntüleri aşağıdaki biçimlerden birine dönüştürün (çizgi çizimler, yarı tonlar ve çizgi/yarı ton kombinasyonları için aşağıda verilen çözünürlük gereksinimlerine dikkat edin):

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Şekil başlıkları; şekillerin altına yazılmalı ve çizelgeler için yukarıda belirtilen yazım kurallarına benzer şekilde, şekil başlıkları hem Türkçe hem de İngilizce hazırlanmalıdır. Şekiller için en büyük boyut, şekil başlığını da içerecek biçimde 16 cm (genişlik) x 22 cm (uzunluk) olmalıdır. Özellikle haritalar, arazi ile ilgili çizimler ve fotoğraflar, sayısal ölçek (1:25000 vb.) kullanılmamalı, metrik sisteme uygun çizgisel ölçekle verilmelidir. Tüm haritalarda kuzey yönü gösterilmelidir. Bölgesel haritalarda, uygun koordinat sistemi (enlem/boylam veya izdüşüm koordinat sistemi) değerleri verilmelidir. Harita açıklamaları (lejand); şekil başlığıyla birlikte değil, şeklin üzerinde yer almalıdır. Şekiller (a), (b) vb. gibi gruplar halinde verilebilir. Bu tür sunumlarda örneğin; Şekil 1a, b'de, veya (Şekil 1c, d) a, b, c, d vb. şeklinde toplu olarak sunulan bir şekil, ayrı sayfalarda basılması yerine, gruplandırılarak aynı sayfada sunulmalıdır.

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Tolga ÇAN

Çukurova University, Engineering Faculty, Geological Engineering Department, 01250 Adana Türkiye

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Ahmetoğlu, A. & Hüsnüoğlu, H. (2022b). Article 2. Full Name of Journal, Vol. (No), pages. DOI number (if available)

Citations in the text:

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A. Journals

A.1. Citing the periodicals:

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Hoek, E. & David, M. (1990). Estimating Mohr–Coulomb friction and cohesion values from Hoek – Brown failure criterion. International Journal of Rock Mechanics, 27(3), 220-229. https://doi.org/10.1016/0148-9062(90)94333-O

A.2. Special cases:

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Ketin, İ. (1949). Son on yılda Türkiye'de vukua gelen büyük depremlerin tektonik ve mekanik neticeleri hakkında. Türkiye Jeoloji Bülteni, 2(1), 1-13. https://dergipark.org.tr/tr/pub/tjb/issue/50279/650044

A.2.2. If the article has an article number:

Açlan, M., Oyan, V. & Köse, O. (2020). Petrogenesis and the evolution of Pliocene Timar basalts in the east of Lake Van, Eastern Anatolia, Turkey: A consequence of the partial melting of a metasomatized spinel–rich lithospheric mantle source. Journal of African Earth Sciences, 168, Article 103844. https://doi.org/10.1016/j.jafrearsci.2020.103844.

B. Proceedings and Abstracts:

Author(s), (Date). Title of paper. Name of Editor(s), Title of Symposium or Congress, (pages). Name of Publisher. DOI number & internet address (If available).

Şanlıyüksel Yücel, D., İleri, B. (2019). Characterization of weak, strafied and clay bearing rock masses. In H. Sözbilir, Ç. Özkaymak, B. Uzel, Ö. Sümer, M. Softa, Ç. Tepe, S. Eski (Eds.), 72nd Geological Congress of Turkey The Proceedings and Abstracts Book, (s.63-64). Chamber of Geological Engineers of Turkey Publications No: 140. https://www.jmo.org.tr/resimler/ekler/174e0f6fa731893_ek.pdf

C. Books:

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Author(s), (Date). Name of the Book. Name of the Publisher. DOI number & internet address (if available).

Pettijohn, F. J., Potter, P. E. & Siever, R. (1987). Sand and Sandstones (2nd ed.). Springer-Verlag New York. https://www.doi.org/10.1007/978-1-4612-1066-5

Ketin, İ. (2016). Genel Jeoloji, Yerbilimlerine Giriş (9. Baskı). İTÜ Vakfı Yayınları.

C.2. Citing of translated books:

Author(s), (Date). Name of the Translated Book. Name of the Publisher. (Original publishing date). DOI number & internet address (If available).

Komatina, M. M. (2011). Tıbbi Jeoloji: Jeolojik Ortamların İnsan Sağlığı Üzerindeki Etkileri (Translator: Y. Örgün ve D. Bayrak). TMMOB Jeoloji Mühendisleri Odası (Original publication date: 2001).

D. Chapter in a book:

Author(s), (Date). Chapter Name. Name of Editors, Name of Book (Page numbers of the chapter). Name of Publisher.

Merriman, R. J. & Frey, M. (1999). Patterns of very low-grade metamorphism in metapelitic rocks. In M. Frey & D. Robinson (Eds.), Low-Grade Metamorphism, (pp. 61-107). Blackwell Sciences Ltd.

E. Reports and Thesis:

E.1. Reports:

Author(s), (Date). Title of report (If any report no). Name of the Organization or Institution, (published or unpublished).

Kellogg, H. E. (1960). Stratigraphic report, Derik-Mardin area Petroleum District V, Southeast Turkey (Rapor no: 1367). TPAO (unpublished).

E.2. Thesis:

Author, (Date). Title of Thesis [published or unpublished & Ph.D. or MSc Thesis]. Name of the Institution or University.

Sönmez, H. (1996). TKİ ELİ Soma Linyitleri açık işletmelerinde eklemli kaya kütlesi içindeki şevlerin duraylılığının değerlendirilmesi [Unpublished Msc Thesis]. Hacettepe Üniversitesi Fen Bilimleri Enstitüsü.

F. Personal Communications:

Sözbilir, H., 2005. Personal communication. Geological Engineering Department of Dokuz Eylül University, İzmir, Turkey.

G. Information Downloaded from the Internet

Name of the Organization, (Date). The web address, and date of access to the website.

KRDAE, (2020, 02, January). Boğaziçi University Kandilli Observatory and Earthquake Research Institute Regional Earthquake-Tsunami Monitoring Center, http://www.gov.tr.

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İçindekiler / *Contents*

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