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EVALUATING ALTERNATIVES TO BEKHMA DAM: INTEGRATED WATER RESOURCES MANAGEMENT FOR SUSTAINABLE DEVELOPMENT IN THE GREATER ZAB BASIN

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ABSTRACT

The Bekhma Dam was once proposed as a massive solution to Iraq's growing water challenges. But after decades of political delays, environmental concerns, and engineering complications, it remains incomplete. Instead of waiting for a project of such scale, this study explores more flexible and sustainable options. Using historical discharge data from the Eski Kalak Gauge Station, machine learning (XGBoost) was applied to project future water availability under changing climate conditions. The model showed a clear downward trend in discharge, indicating a dominant dry pattern in the coming decades and reinforcing the urgency of adaptive planning. In response, four upstream dam sites were identified through GIS and DEM analysis and evaluated based on reservoir capacity, topography, and regional fit. Bekhma itself was also reconsidered this time as a scaled-down version supported by those smaller alternatives. The idea is simple: by capturing floods and sediment in the upper basin, we can reduce Bekhma's dead storage requirement and make those construction more realistic. This integrated approach could deliver the key benefits water security, storage, flood mitigation while reducing cost, social impact, and structural risk. Importantly, the study clarifies that these alternatives are not a complete replacement for Bekhma, but rather a practical and scalable support system to strengthen resilience. The study argues that combining predictive hydrology with decentralized infrastructure offers a smarter path forward for the Greater Zab Basin. Based on these findings, the study recommends adopting the proposed upstream alternatives alongside a reduced Bekhma structure to create a flexible, climate-resilient water management system.

Keywords: machine learning, GIS, bekhma dam, discharge forecasting, reservoir alternatives, greater zab, water scarcity.

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INTRODUCTION

Iraq's water crisis is no longer a future threat it's already happening. Studies have revealed that under numerous shared socioeconomic pathways, large regions including the Middle East are projected to face severe water scarceness risks in coming periods (Hanasaki, et al. 2013)."The Greater Zab River, one of the last major unregulated tributaries of the Tigris, holds great potential for solving some of these pressing issues. One of the largest proposed water infrastructure projects in Iraq, the Bekhma Dam, was designed to harness this potential by providing flood control, hydropower, and a massive 17 billion cubic meters of storage (Abdulwahid, et al. 2020, Al-Ansari, et al. 2021, Mohammed, and Ahmed, 2021). But despite decades of

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planning, the dam remains unbuilt, raising questions not only about when it might be completed but whether its original design still makes sense in today's context. Multiple studies have acknowledged the promise of Bekhma (Al-Khudhairi, and Al-Ansari, 2020, Al-Muqdadi, and Hussien 2023). However, they also point to serious concerns. On the technical side, the Greater Zab Basin is prone to high sediment loads due to steep topography and fragile geology conditions that would rapidly fill the dam's dead storage, shorten its lifespan, and reduce its operational capacity (ICOLD. 2019). Recent studies focused on dam performance across Northern Iraq, evaluations have shown how catchment characteristics and dam height play a major role in storage potential and efficiency)(Al-Khudhairi, and Al-Ansari, 2020, Al-Saadi, et al. 2017, Mohammadi, and Ghafouri, 2021). On the social side, the dam's full construction would displace communities, flood agricultural land, and cause irreversible ecological change (Al-Muqdadi, and Hussien, 2023, Al-Taie, et al. 2021). Economically, the scale and cost of the project have become even harder to justify amid regional instability. And geopolitically, reduced flows from Turkey's upstream dams on the Tigris have introduced uncertainty around whether Bekhma could ever function as originally planned (Rahi, and Halihan, 2010). So what has the academic community proposed? Most discussions either revisit the original plans or suggest broad Integrated Water Resources Management (IWRM) approaches without offering tangible alternatives to Bekhma's design. Others focus solely on the climate risks, with limited integration of engineering feasibility. Very few studies attempt to combine discharge forecasting, machine learning, and multi-site reservoir planning into one strategic framework. This is the gap where our study aims to contribute. Rather than asking whether the Bekhma Dam should be completed or not, we ask a more practical question: Can its function be fulfilled differently more flexibly, more sustainably, and more realistically? To do this, we combine long-term hydrological analysis with modern tools, applying the XGBoost machine learning algorithm to historical discharge records from the Eski Kalak Gage Station (Khosravi, et al. 2018, Mahmood, and Abdullah, 2022). This gives us a clear picture of how the river's flow might behave under future climate stress. From there, we examine four new upstream dam sites and reassess Bekhma itself at a reduced height both in terms of feasibility and how they can collectively achieve water security goals without the same level of environmental and political baggage. Our approach is grounded in GIS and Digital Elevation Models (DEMs) to determine the potential storage and elevation profiles of each alternative site. These physical evaluations are then aligned with IWRM principles, focusing on resilience, adaptability, and trade-offs. We do not claim to have a single perfect solution. Instead, we offer a structured argument that blends predictive data science, engineering logic, and regional constraints into a plan of action. The goal of this paper is to present a new way of thinking about water security in the Greater Zab Basin. Not through one massive project that might never be realized but through a combination of smarter, smaller, and more adaptable systems that reflect the future, not the past.

MATERIALS AND METHOD

The Greater Zab River Basin (GZRB), the largest tributary of the Tigris River, covers around 26,500 km² and plays a vital role in the water security of Iraq and the broader Mesopotamian region. It originates in the Zagros Mountains in eastern Turkey and flows southeast through the Kurdistan Region of Iraq before joining the Tigris River. Along this path, it supports the water demands of millions

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from agriculture and municipal use to hydropower and ecosystem sustenance. However, the region experiences significant hydrological variability, with spring snowmelt resulting in peak flows and harshly low discharges during dry summers. Eski Kalak Gauge Station records reveal extreme fluctuations, (Abbas, et al. 2020, Al-Muqdadi, and Hussien, 2023), raising red flags about future water reliability amid climate change. One of the most ambitious responses to these challenges was the proposed Bekhma Dam, located strategically on the Greater Zab River. Planned to rise 230 meters high and store 17 billion cubic meters of water, the dam was envisioned as Iraq's flagship hydropower and water storage project (Abdulwahid, et al. 2020). It promised over 1,500 MW of electricity generation and a critical flood regulation but it was never completed. Construction was halted in the early 1990s due to geopolitical tensions, funding shortages, and widespread criticism of its environmental and social impacts (Al-Khudhairi, and Al-Ansari 2020). Critically, the river carries an estimated 6.6 million tons/year of sediment (Al-Ansari, et al. 2021), which would pose serious operational risks without dedicated sediment management. The initial design of Bekhma included a dead storage capacity of 4 BCM, representing nearly 24% of its total volume. Such high dead storage raises concerns about long-term water efficiency and loss of usable capacity, particularly in a region where every drop counts. To tackle this issue, our study examines whether strategically placed smaller dams upstream, along with a reduced-height version of Bekhma, could serve as a more sustainable alternative. This approach, illustrated in Table 1, aims to minimize dead storage, reduce submergence impacts, and enhance flexibility in integrated water resource planning. By redistributing water storage across multiple points in the basin, while still considering the original Bekhma location, we aim to improve resilience, reduce ecological and social disruption, and strengthen the adaptive capacity of the entire system under future climate uncertainty (Al-Saadi, et al. 2017**,** Das, et al. 2020).

Table 1. Key Hydrological and Design Parameters of Bekhma Dam

Parameter	Value
Proposed Height (m)	**230**
Crest Length (m)	**530**
Storage Capacity (BCM)	**17.0**
Dead Storage Volume (BCM)	**4.0**
Power Generation (MW)	**1,500**
Sediment Load (Million Tons/Year)	**6.6**

This study integrates machine learning forecasting with spatial analysis to evaluate the feasibility of alternative dams as a strategic response to projected discharge declines in the Greater Zab Basin. The methodological approach unfolds in three stages: hydrological trend modeling, spatial selection of potential dam sites, and comparative evaluation based on hydrological and topographic criteria. To begin, discharge trend modeling was conducted using XGBoost, a machine learning algorithm renowned for its effectiveness in handling non-linear relationships and time-series forecasting (Ameen,and Tawash, 2021). Machine learning models like XGBoost have confirmed extremely effective for hydrological predictions, presenting higher performance in trend recognition and parameter optimization (Duan, et al. 2021)." The algorithm was trained on annual discharge data from the Eski Kalak Gage Station, which lies downstream of the proposed Bekhma Dam and provides a representative hydrological signal for the Greater Zab Basin. Historical records from 1932 to 2023 were used to build and validate the model. Evaluation metrics such as Root Mean Square Error (RMSE), coefficient of determination (R^2), and Nash–Sutcliffe Efficiency (NSE) were used to verify model accuracy (Choubin, et al. 2019**,** Dawood, and

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Mahdi, 2022). The trained model produced future discharge predictions extending to 2050. The declining trend revealed by the model was a key trigger for initiating an investigation into new water storage options. Following the identification of future water stress, spatial analysis tools were applied to explore alternative dam sites upstream of Bekhma. GIS and remote sensing approaches have previously been applied to sedimentation analysis and reservoir assessment, demonstrating their effectiveness in optimizing dam site selection (Al-Khudhairi, and Al-Ansari, 2020, Fan, et al. 2020, Khosravi, et al. 2018). Using a 30-meter resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM), the study delineated the Greater Zab Basin and extracted hydrologically significant features, including flow direction, accumulation, and stream orders. These datasets were processed in ArcGIS Pro to identify potential storage sites based on valley geometry, elevation, and proximity to the main channel. Preceding studies in Erbil have effectively applied GIS-based suitability assessments to guide dam development decisions, strengthening the method's local application and efficiency. Five key locations were identified: the original Bekhma site and four upstream alternatives (labeled Dam1 to Dam4). These locations were selected for their potential to store water efficiently while minimizing environmental and social disturbance. GIS-based multi-criteria decision analysis (MCDA) methods have been efficiently used in similar dam site assessments, supporting the method engaged in this study (Saleh, and Khlaif, 2021). The spatial layout of these proposed sites is presented in Figure 1. To compare these alternatives, a set of topographic and hydrological criteria was applied. Storage capacity estimates were calculated using DEM-based reservoir simulation, which allowed for a volume-elevation relationship at each site (Liu, et al. 2017). In parallel, catchment area sizes were extracted using watershed delineation tools, enabling a first-order approximation of the water contribution potential. Furthermore, valley slope and cross-section geometry were examined to assess structural feasibility (Mahmood, and Abdullah, 2022). While environmental parameters such as land use and settlement proximity were acknowledged, their assessment was limited by data availability and will be considered in future stages of the project. The original Bekhma Dam was also included in this evaluation, but under a modified scenario with reduced dam height. This approach is grounded in the hypothesis that building smaller upstream dams could reduce sediment inflow and active reservoir requirements at Bekhma. Such a strategy could make it possible to lower Bekhma's height, thereby reducing its footprint, dead storage volume, and environmental impact. However, the optimization of these relationships will require further research, particularly regarding sediment dynamics, which are not addressed in this paper due to a lack of consistent data. Instead, sediment transport, dead storage mitigation, and dam safety concerns will be handled in a subsequent study that builds upon the present findings.

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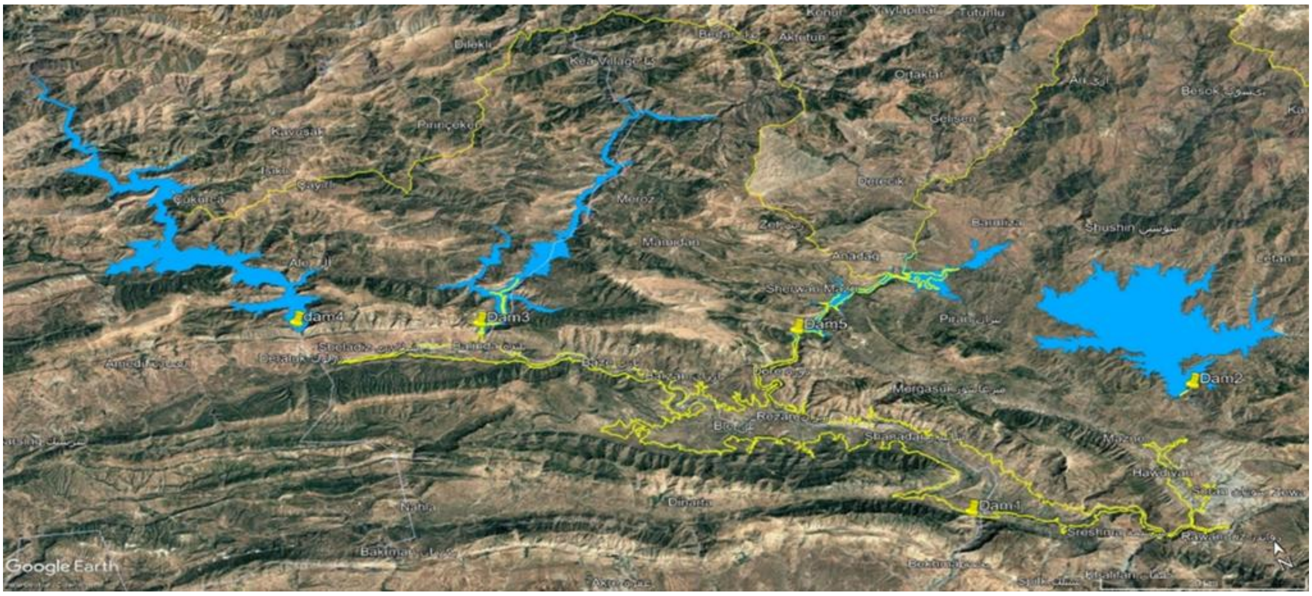

Figure 1. A map showing the Greater Zab Basin, the planned Bekhma Dam site, and alternative dam locations within the basin

RESULTS AND DISCUSSION

Analysis of the historical discharge data from the Eski Kalak station on the Greater Zab River reveals a pronounced declining trend in annual flow. As shown in **Figure 2**, both linear and polynomial projections indicate a continuous reduction in average discharge, with polynomial models suggesting a sharper decline towards mid-century. The historical mean discharge was approximately **371.09 m³/s**, while trend analysis (**Figure 3**) indicates a statistically significant annual decrease of **-2.2048 m³/s per year** (p = 0.0001), emphasizing the region's increasing vulnerability to water scarcity (Das, et al. 2020, Liu, et al. 2017).

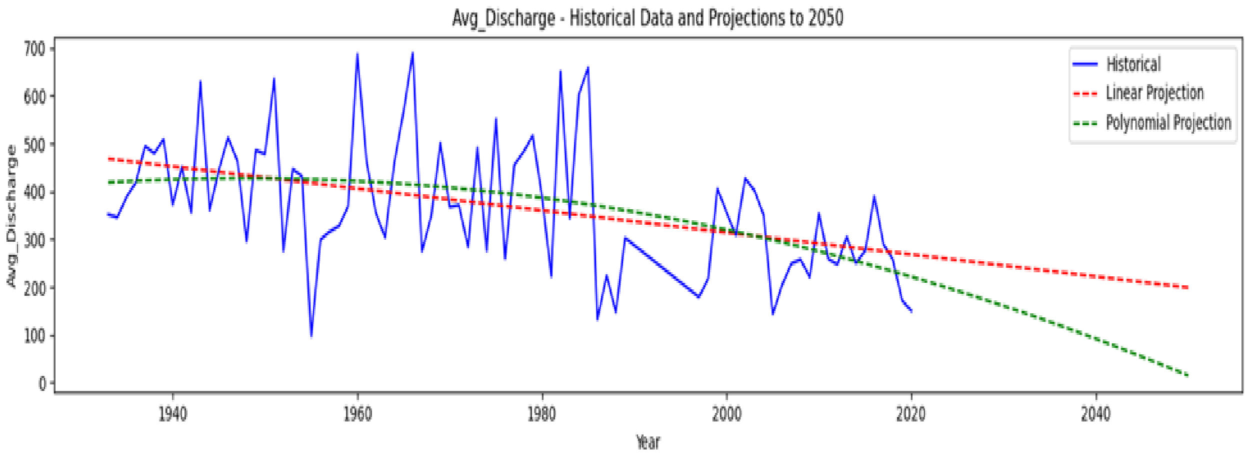

Figure 2. Linear and polynomial projections for average discharge

A five-year moving average was applied to further smooth the discharge variability and reinforce the downward trend. This decline becomes especially evident after the year 2000, supporting the urgent need for strategic intervention. To address the growing uncertainty under future climate conditions, the **XGBoost** machine learning model was employed to forecast discharge trends through 2050 (Fan, et al.2020). The model was trained on historical data and validated for performance using R² and RMSE metrics as detailed in **Table 2**. This modeling approach aligns with prior studies highlighting the

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suitability of machine learning techniques for rainfall-runoff and streamflow forecasting in arid and semi-arid regions (Mohsenipour, and Shahabi, 2020, Yaseen, et al. 2016).

Table 2. XGBoost Model Performance metrics

Metric	Training	Testing
R^2	0.92	0.89
RMSE (m^3/s)	14.7	17.3
NSE	0.91	0.88

As illustrated in Figure 4, XGBoost projections show a 63.3% probability of below-average discharge events dominating the next three decades, indicating that 6 to 7 years out of every 10 may experience diminished water availability. Probability of below-average discharge events was estimated from the historical mean annual discharge that was first calculated from observed records at the Eski Kalak Gage Station. Then, annual discharge values for the future periods (2024–2030, 2031–2040, and 2041–2050) were predicted by means of the trained XGBoost model. For each period, the number of years where the predicted annual discharge fell below the historical mean was totaled and divided by the total number of years in that period. For example, the 63.3% of the modelled years showed discharge values below the historical mean was calculated during 2041–2050, representing a high probability of progressively dry years (Dawood, and Mahdi, 2022, Mohammed, and Ahmed, 2021, Pahlavan-Rad, and Soltani, 2017). Such apprehensions have been resonated in topical national assessments that highlight the urgency of climate-adaptive infrastructure to protected Iraq's future water obtainability (World Bank. 2021). These results present a dangerous argument for practical water storage planning. The predictable inconsistency and potential decline in discharge could compromise the region’s hydropower potential, irrigation reliability, and overall water security, mainly in downstream areas like Erbil. The long-term discharge drop, if not addressed with adaptive infrastructure, could lead to complete stress across multiple sectors. The observed drop in discharge and climate-driven variability line up with regional findings on river systems across Iraq, where water stress has become more recurrent and severe (Mahmood, and Abdullah, 2022, Masud, et al. 2018, Mohammadi, and Ghafouri, 2021). Similar findings have been observed in Kurdistan region Iraq, where climate variability has been shown to significantly affect dam operations and reservoir performance, requiring more flexible and predictive water management policies (Zolghadr-Asli, and Naghipour, 2021,).

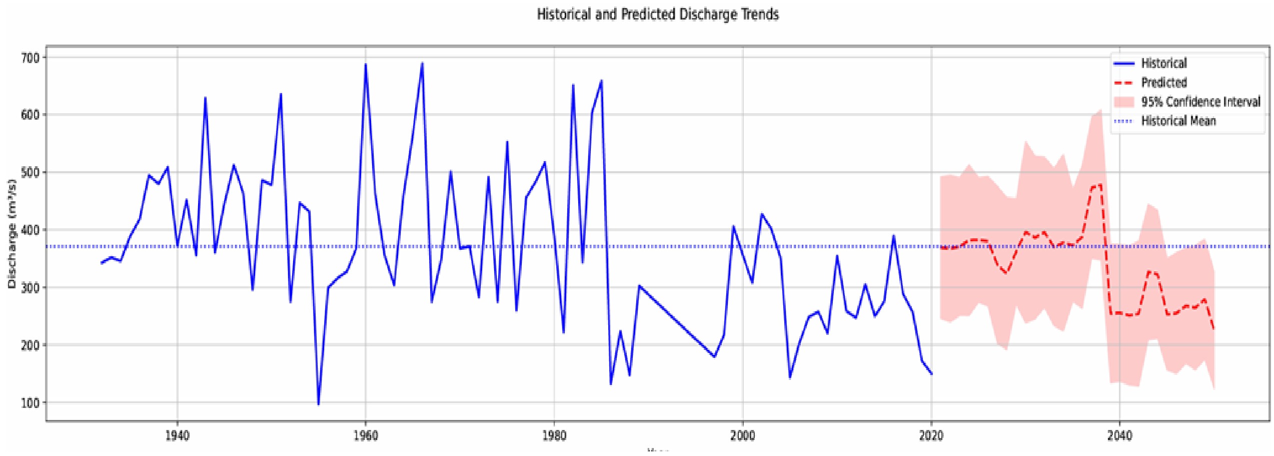

Figure 3. Historical data and XGBoost-predicted discharge with 95% confidence interval

Following the discharge modeling using XGBoost, which confirmed a clear declining trend of ~2.2 m^3/s per year in the Greater Zab River, there is an urgent need for a more

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adaptable water infrastructure strategy. This is particularly important given that future discharge is expected to fall below historical averages in 63.3% of years by 2050 (Figure 4), intensifying seasonal water shortages and reservoir operational challenges. The originally designed Bekhma Dam, at 600 meters elevation and 230 meters high, provides an impressive 17.99 BCM of storage (Table 3) and (Figure 4). However, approximately 4 BCM is classified as dead storage (Figure 5), resulting in inefficient water use and potential sedimentation challenges (Al-Khudhairi, Al-Ansari, 2020, Choubin, et al. 2019,). To address this, we explored two key design shifts: First, reducing Bekhma's elevation to 540 m, which provides 7.19 BCM of live storage. Second, introducing four alternative upstream dams Derana (D2), Sheladiz (D3), Deraluk (D4), and Dore (D5) to compensate for the lost volume. When combined, the reduced Bekhma (7.19 BCM) and the four alternative dams (9.40 BCM) offer a total of 16.59 BCM, equating to 92.2% of the original Bekhma plan, while entirely avoiding the 4 BCM dead storage (Mohammadi, and Ghafouri, 2021, Sayl, and Jothityangkoon, 2022). Similar conclusions were drawn from comparative studies of Iraq's major dams under projected climate scenarios, highlighting the need to reconsider traditional dam planning in favor of adaptable, region-specific strategies (Salah, and Khalil, 2020).

Table 3. Storage Capacity and Estimated Dam Heights of Bekhma and Alternatives

Site	Elevation (m)	Height (approx. m)	Storage Volume (BCM)
Bekhma (D1)	600	230	17.99
Derana (D2)	880	200	3.93
Sheladiz (D3)	770	200	2.26
Deraluk (D4)	860	200	2.25
Dore (D5)	640	120	0.96
Total (Alt. 2–5)	—	—	9.40

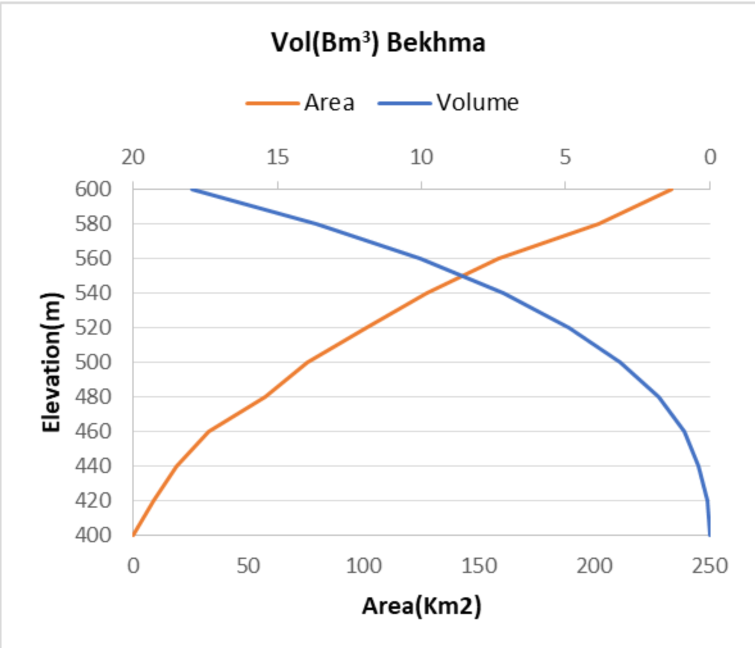

Figure 4. Volume–Elevation Curve of Bekhma Dam Site

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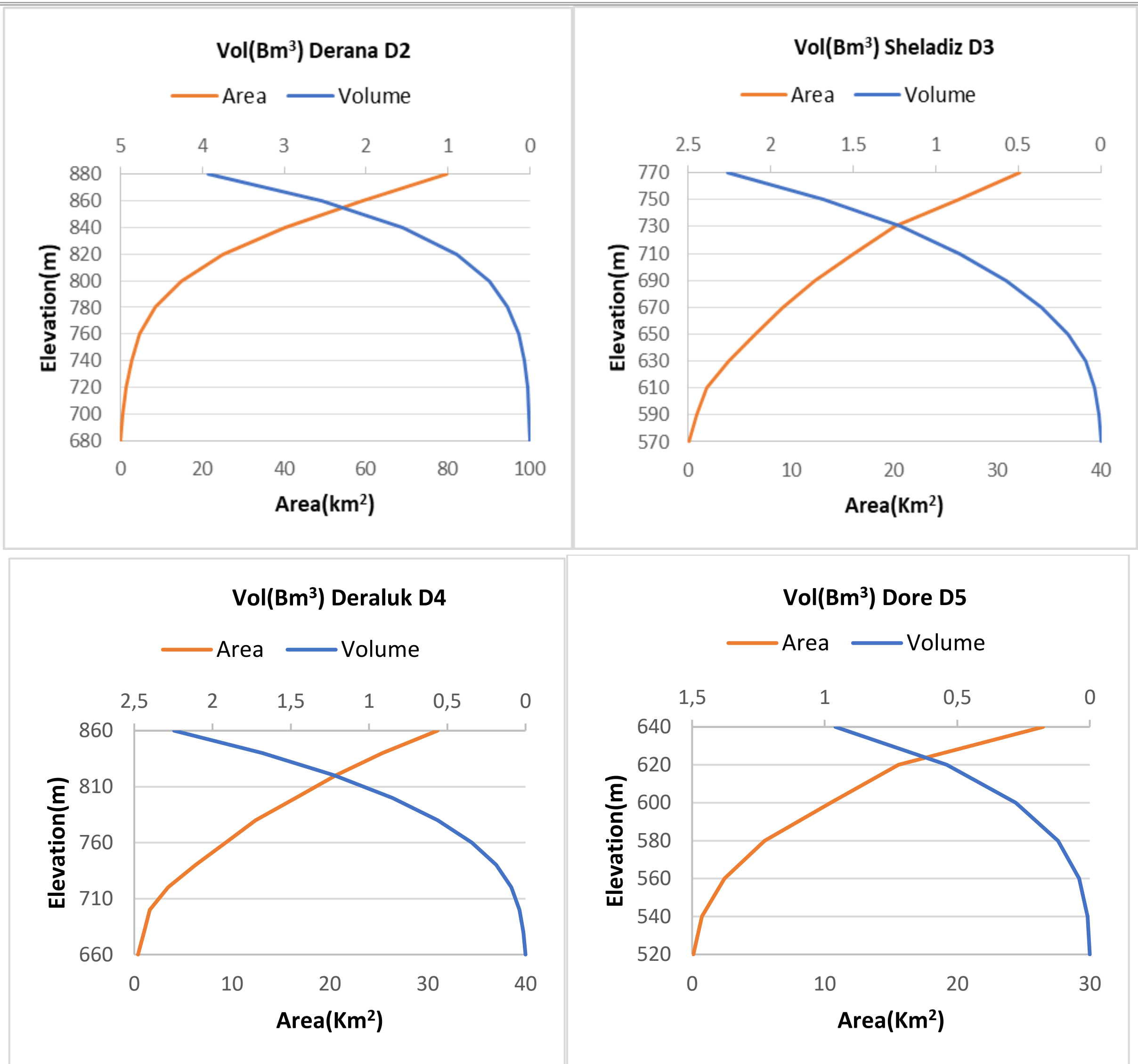

Figure. 5 Elevation–Volume Graphs for Bekhma Dam Alternatives Sites(Derana D2, Sheladiz D3, Deraluk D4 and Dore D5)

Economically, the cost of Bekhma Dam due to its massive scale and geological challenges has long been cited as a barrier to completion (Altinbilek, 2002). Similar decisions were drawn from virtual studies of Iraq's major dams under predictable climate scenarios, highlighting the necessity to reassess traditional dam planning in service of adaptable, region-specific strategies (Salah, and Khalil, 2020)."Based on international benchmarks, the average cost is estimated at **$0.25 billion per BCM** for large dams like Bekhma and **$0.35 billion per BCM** for smaller alternatives (World Bank, 2021; ICOLD, 2019). This yields in the following cost estimates shown in Table 4:

Table 4. Cost Comparison of Bekhma and Proposed Alternatives

Dam Name	Volume (BCM)	Estimated Cost (USD Billion)
Bekhma (Full)	17.99	4.50
Bekhma (Reduced)	7.19	1.80
Derana	3.93	1.38
Sheladiz	2.26	0.79
Deraluk	2.25	0.79
Dore	0.96	0.34
Alt. System	16.59	5.10

Cost per BCM: $0.25 billion for Bekhma (large-scale), $0.35 billion for alternatives (smaller dams), based on average unit costs reported by ICOLD (2019) and World Bank (2021).

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While the decentralized system has a slightly higher cost per BCM; it offers key advantages: Improved sediment control: alternatives upstream can trap sediment before it reaches Bekhma. Reduced displacement risk: smaller reservoirs avoid submerging large towns and agricultural lands. Better water distribution: spreading storage improves regional equity and redundancy in case of dam failure. Moreover, building multiple small dams allows phased investment, reducing financial risk and increasing political feasibility. From a technical standpoint, many smaller sites are located in elevated valleys, making construction less complex and less socially disruptive. These dams may also function as buffer storage during high flows, enhancing seasonal regulation for downstream communities. From an IWRM perspective, such a decentralized system encourages local water governance, resilience against climate variability, and eventual integration with existing networks. Furthermore, lowering Bekhma's design makes it more likely to be completed after decades of abandonment, especially since the original high dam design has faced sedimentation, instability, and regional geopolitical concerns (Abbas, et al. 2020, Yaseen, et al. 2016).

CONCLUSION

This study assessed the feasibility of implementing a distributed dam strategy as an alternative to the originally proposed Bekhma Dam on the Greater Zab River in Iraq. Leveraging historical discharge analysis and future projections using the XGBoost machine learning model, the study confirmed a clear and statistically significant downward trend in annual discharge, with a 63.3% probability that values will fall below the historical average by 2050. These findings amplify concern over the long-term water security of the Kurdistan Region of Iraq (KRG), especially under continued climate change pressure. The proposed solution reducing Bekhma's elevation to 540 meters while constructing four additional upstream dams emerged as a technically and economically viable strategy. This hybrid configuration retains 92.2% of the original storage capacity of Bekhma (16.59 BCM vs. 17.99 BCM) while eliminating 4 BCM of dead storage, reducing ecological and social disruption, and promoting phased, adaptive investment. Although the overall system may cost slightly more per unit volume, it offers greater resilience, distributed benefits, and alignment with Integrated Water Resources Management (IWRM) principles. By decentralizing water infrastructure, the strategy reduces sedimentation risk at Bekhma, avoids displacement in sensitive downstream zones, and improves transboundary water buffering capacity. Furthermore, the use of machine learning tools like XGBoost proved critical in capturing non-linear hydrological behavior, enabling more robust forecasting than traditional statistical methods. It is important to emphasize that the long-term success of this approach depends on conducting future work including sediment transport analysis, dam safety evaluation, cost benefit optimization, and regional cooperation frameworks. In particular, adapting water management under uncertain climate futures will require not only infrastructure investments but also institutional reforms and data-sharing agreements across borders. Ultimately, the evidence points to a practical conclusion: there is urgent need to implement Bekhma Dam with revised specifications or pursue its alternatives upstream. Both options can ensure water security if integrated into a comprehensive, climate-informed strategy that is flexible, decentralized, and people-centered. A strategic shift toward decentralized water storage and integrated management aligns with emerging IWRM approaches adopted in Iraq to address both environmental and institutional challenges (Zolghadr-Asli, and Naghipour, 2021).

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تقييم البدائل المقترحة لسد بيخمة: الإدارة المتكاملة للموارد المائية من أجل التنمية المستدامة في حوض نهر الزاب الأكبر

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المستخلص

لقد طرح سد بيخمة في السابق كحل ضخم لمواجهة التحديات المائية المتزايدة في العراق، لكنه ظل غير مكتمل لعدة عقود بسبب التأخيرات السياسية والمعوقات البيئية والتعقيدات الهندسية. وبدلًا من انتظار مشروع بهذا الحجم، تستكشف هذه الدراسة خيارات أكثر مرونة واستدامة من خلال استخدام بيانات تصريف محطة أسكي كلك وتطبيق تقنية تعلّم الآلة (XGBoost) للتنبؤ بتوفر المياه مستقبلًا في ظل التغيرات المناخية. أظهرت نتائج النموذج اتجاهًا واضحًا نحو انخفاض التصريف، وأكدت هيمنة الظروف الجافة على المدى المتوسط، مما يعزز الحاجة إلى تخطيط تكيفي سريع. واستجابة لذلك، تم تحديد أربعة مواقع للسدود صغيرة في أعالي الحوض باستخدام نظم المعلومات الجغرافية (GIS) ونماذج الارتفاع الرقمية (DEM)، وتقييمها من حيث السعة التخزينية والطبوغرافيا والملاءمة الإقليمية . كما أُعيد النظر في سد بيخمة نفسه، ولكن هذه المرة بنسخة منخفضة تعتمد على بدائل صغيرة. الفكرة ببساطة: من خلال حجز الفيضانات والرسوبيات في أعلى الحوض، يمكن تقليل حجم التخزين الميت في بيخمة، وجعل بنائه أكثر واقعية. هذا النهج المتكامل يمكن أن يوفر الفوائد الرئيسية نفسها لأمن المياه والتقليل من تكاليف التخزين، مع تقليل الكلفة والمخاطر الاجتماعية والإنشائية .وتوضح الدراسة أن هذه البدائل لا تهدف فقط إلى استبدال سد بيخمة، بل تمثل نظامًا داعمًا أكثر مرونة وكفاءة، وتعدل الدراسة بأن الجمع بين التنبؤات الهيدرولوجية والبنية اللامركزية يمثل مسارًا أكثر ذكاءً لمستقبل حوض الزاب الأعلى .وبناءً على ذلك، توصي الدراسة باعتماد استراتيجية سدود صغيرة متعددة كبديل عملي مستدام لمواجهة التحديات المائية في المنطقة.

الكلمات المفتاحية: التعلم الآلي, نظم المعلومات الجغرافية، سد بيخمة، التنبؤ بالتصريف، بدائل السدود، نهر الزاب، ندرة المياه.