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Artificial Intelligence, Environmental Challenges, and Sustainability in Iraq

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Abstract
This review of literature focuses on the deployment of transparent, ethical AI technologies in environmental domains (climate change, hydrology, pollution, and biodiversity) in Iraq, advocating a pivotal role for AI in advancing a resilient, sustainable ecology. Issues related to Iraq's preparedness to embrace the AI and IoT revolution were discussed, as these technologies are globally shaping sectors such as health, finance, and the environment. An attempt was made to explore the complex conundrum of introducing AI technologies into the even more complex challenges posed by the weak digital and ICT infrastructure, with recognition that scientists have already considered AI models in the investigation of environmental domains as an alternative to traditional approaches to improve predictability and decision-making in search of sustainable solutions.

Keywords: Artificial Intelligence, IoT, Remote sensing platform, GIS, Climate Change, Hydrology, Pollution, Biodiversity, Waste, Ethics.

1. Introduction

Accurate detection and forecasting of environmental challenges are crucial for developing effective mitigation, adaptation, and control strategies that reduce their impact on public health, society, the economy, and the environment as a whole. Moreover, traditional approaches have often failed to produce a significant effect on environmental problems, particularly in countries such as Iraq, where there is an urgent need to implement modern methods that make a difference in managing environmental risks [1].

Adopting groundbreaking technologies, such as Artificial Intelligence, in environmental management is more than just a technical upgrade; it represents a significant shift in approach. It demands substantial structural and cultural shifts, as well as a transformation in mindset. The successful integration of AI hinges on a collaborative approach that unites diverse disciplines and stakeholders within a shared framework. This collaboration is essential to guiding the deployment of AI tools in a way that thoughtfully addresses ethical, social, and environmental considerations. Moreover, building a foundation for AI use in environmental domains must be guided by principles that protect the public interest while harnessing the benefits of technological advances. By adopting a holistic approach, Iraq will be better positioned to harness AI's full potential for sustainable development and robust environmental governance [2].

Undoubtedly, Obstacles will emerge and are already visible that could thwart the introduction of AI, such as poor digital infrastructure, weak governance, untrained staff, and limited investment. As a consequence, efforts to incorporate the digital revolution into environmental management are delayed at the initial stages of policy implementation [3].]

Since John McCarthy coined the term "artificial intelligence" in 1955, AI technologies—including deep learning and neural networks—have played an increasingly important role in environmental research and applications, owing to the capability to rapidly and efficiently analyse vast datasets, uncovering patterns missed by traditional statistical methods or human analysis [4].

Recent work by Mijwil, M. M., et al. [5] has highlighted the growing application of artificial intelligence across various sectors, including finance, military, healthcare, and, indeed, the environment, where precise prediction and forecasting are crucial. AI models powered by deep learning are particularly effective at recognising images, analysing texts, and detecting patterns, all of which support sound decision-making and help reduce human error. The authors conclude that the future shaped by AI is already underway, as these systems demonstrate an ability to learn and improve independently, without constant human input. Moreover, both environmental and health sectors in Iraq stand to gain significantly from this AI-driven transformation. AI models can help define environmental priorities, guide decision-making, and provide accurate predictions—though the full extent of their potential remains to be determined.

Nevertheless, problems arise when digital infrastructure is weak or lacking. Poor datasets can cause deep learning algorithms to underperform, a phenomenon known as "overfitting," which tends to occur when an AI model excels on its training data but performs poorly on limited or unrepresentative datasets. To tackle overfitting, data engineers employ techniques such as cross-validation — splitting the data into training and validation sets to monitor performance — and simpler models with fewer parameters to improve generalizability. These strategies are essential for ensuring that AI tools can deliver reliable outcomes [6].

1.1 Iraq and the AI Revolution

The pertinent question of whether Iraq is ready to adopt AI applications in environmental and health research is beyond the scope of this paper. However, it is worth noting that Alalaq, A.S. examined Iraq's preparedness to incorporate AI by applying the Oxford Insights Government AI Readiness Index, 2024 edition, as a global benchmark [7]. The study concludes with several recommendations for improving Iraq's readiness for AI technology. In a similar vein, the United Nations Development Programme (UNDP) released a report that provides an overview of the digital maturity landscape in the Iraqi public sector as of 2023. The report indicates a weak outcome, with only 37% of digital goals related to information and communication technology achieved [8].

Nevertheless, a significant landmark was reached in 2023, with the inception of the "Iraqi National Strategy for Artificial Intelligence (INSAI), to address the challenges associated with introducing artificial intelligence (AI) across various sectors, including health and environmental. In essence, it represents a comprehensive roadmap, supported by academia, industry, and government, to build national AI capabilities and ensure AI is deployed ethically and responsibly [9].

A central theme of the INSAI strategy is future investment in robust digital infrastructure (extensive national datasets, high-performance computing, reliable cloud data storage systems, widespread internet access, and the development of a skilled AI workforce). With adequate support, funding, and human resources, Iraqi experts will be well-positioned to harness AI's potential by developing versatile solutions tailored to environmental, health, and other domains.

A paradox will surely emerge as deep learning models become more advanced, and their data requirements become increasingly complex. Meeting these demands will be vital for the continued success and reliability of AI-driven applications and environmental initiatives in Iraq.

During the transitional period, Iraqi environmental scientists are already utilising "open sources" to complement the limited local and historical data. Open sources are platforms that deploy remote sensors to detect and measure electromagnetic radiation—either reflected from or emitted by objects on Earth, like water, vegetation, soil, and can detect Surface structure, elevation, moisture, measure Surface temperature, Vegetation health, Soil moisture, and Atmospheric gases, all of which are important in environmental research [10].

Globally, satellite remote sensing platforms play a pivotal role in environmental research, with data sets widely accessible through resources such as NASA Earth data and the Copernicus platform (the leading European remote sensing platform). They are an invaluable source of comprehensive spatial and temporal data across several domains. In Climate Sciences, Satellite sensors monitor sea surface temperatures and greenhouse gas emissions, providing critical information for understanding climate patterns and changes. Equally, they can track deforestation, glacier retreat, and pollution. Other uses include smart agriculture, where crop health is assessed, soil moisture is measured, and yields are predicted, enabling more effective and sustainable agricultural practices [11].

The other widely used remote sensing platform is Geographic Information Systems (GIS) integrated with artificial intelligence. GIS is a robust technology capable of capturing, storing, analysing, and visualising spatial or geographic data, creating digital maps enhanced with descriptive details such as surface water data and weather patterns, or three-dimensional models, and interactive dashboards. These capabilities make GIS indispensable for intelligent urban planning, smart agriculture, pollution monitoring, disaster management, and public health initiatives—including disease tracking, resource allocation, and analysis of healthcare access [12]. With appropriate investment and capacity building, researchers could achieve a potential breakthrough in Iraq by developing systems that integrate a remote sensor platform with real-time data through Internet of Things (IoT) sensors connected to a central national data centre with dependable cloud storage. This technology will collect data directly from key locations—on land, in water, or in the atmosphere—using ground-based, airborne, or marine IoT sensors. These real-time measurements are crucial for calibrating and validating remote sensing data, reducing errors in predictive modelling, and providing reliable reference points for environmental studies.

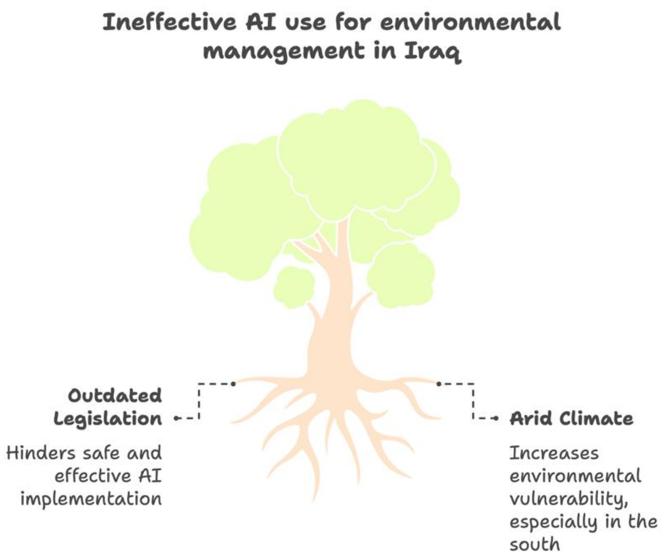
Integrating IoT applications with advanced machine learning and artificial intelligence presents unparalleled opportunities for environmental applications, equipping decision-makers with crucial tools to achieve improved outcomes. Panduman, Y.Y.F. et al, presented a comprehensive review of IoT applications integrated with AI techniques and proposed a design of an IoT application server platform called SEMAR (Smart Environmental Monitoring and Analytics in Real-Time), integrated with AI, can collect, display, and analyse sensor data on a single platform supported by cloud technology, with built-in functions for data communications, aggregations, synchronisations, and classifications using machine learning algorithms [13].

2. AI Use in Iraqi Environmental Research

Iraq lies at 33°00′N, 44°00′E, covering a total area of 437,072 square kilometres, with less than 10% of the area covered by water. Geographically, the country's landforms are divided into four principal regions: the Mountain Region, Plateau and Hills Regions, the Mesopotamian Plain, and the Jazeera and Western Plateau. Iraq is predominantly characterised by an arid to semi-arid climate, particularly in its central and southern regions. The southern climatic zone is identified as the region with the highest environmental vulnerability in Iraq [14, 15].

Numerous published studies have used ANN-based approaches to manage and adapt to climate change [16]. However, to fully harness the potential of AI in environmental control and management, a robust regulatory framework is required to ensure practical and ethical implementation, ultimately leading to life preservation and resource optimisation [16]. This is very much an issue for Iraq, too. The Iraq Environmental Act 2009 is outdated and requires amendment to allow safe and effective use of AI Technologies in environmental domains.

Moreover, over the last three decades, several studies have used AI models to assess the quality and extent of environmental degradation in Iraq. The following sections highlight published research on the applications of AI models across various environmental domains in Iraq.



2.1 The Climate Change Domain

Climate change is a clear and present threat, casting a long shadow over Iraq; hence the potential role of artificial intelligence (AI) as a powerful transformative technology capable supporting strategies to confronting climate change challenges has received considerable interest by environmental scientists in search of effective sustainable mitigation and adaptation policies in harmony with Iraq environmental and social circumstances, by virtue of AI ability to monitor and, forecast climatic events, and optimise resource use.

The Sixth Assessment Report (AR6) comprehensively summarises current knowledge on climate change, including its widespread impacts and risks, based on peer-reviewed scientific, technical, and socio-economic studies [17]. Furthermore, Iraq has been listed as the fifth-worst-affected country by climate change [18].

In Iraq, the features of climate change include rising temperatures, reduced and erratic rainfall, increased water scarcity and droughts, frequent sand and dust storms, flooding, and threats to the integrity of the biosphere, all of which have detrimental effects on humans, biodiversity, and ecosystems [19].

Cowls, J, et al. explored the role of AI technologies in improving and expanding the current understanding of climate change, aiming to support the adoption of efficient adaptation and mitigation policies [20]. The authors emphasised the importance of providing adequate resources to facilitate the successful integration of AI in environmental management.

The two main approaches to deal with climate change are mitigation (by reduction of greenhouse emissions and or increased capability of processes that remove these gases from the atmosphere) and adaptation measures (plans to increase resilience and reduce vulnerability of the communities and ecosystem to resist the adverse effects of climate change) [21].

Fouad H. Saeed et al. explored a Sustainable Adaptation Plan in Response to Climate Change and Population Growth in the Iraqi Part of the Tigris River by evaluating the balance between projected water resources and water demand through 2080 [22].

A significant feature of climate change in southern Iraq is the record-breaking extreme high temperatures, including some of the highest temperatures globally conducted a long-term trend analysis of Iraqi recorded temperatures [23-25]. They concluded that the temperature would continue to rise and that dry areas would become drier, particularly in the southern climatic zone, which is the most vulnerable in Iraq. However, these studies used traditional statistical methods. As an example of using an AI model for accurate temperature prediction, Mustafa, M. S., & Al-Jawadi, B. A., concluded that conventional forecasting methods, such as statistical and shallow machine learning models (models that rely on a limited number of layers), struggle to address the complex time-dependent characteristics of meteorological data [26]. They proposed an alternative system based on a deep machine learning Neural Network (ANN) to improve temperature forecasting for the three large cities in northern Iraq (Dohuk, Erbil, and Mosul). The chosen AI model can learn both short-term and seasonal weather trends. They used a meteorological dataset spanning 24 years (2000-2024) with five significant variables: temperature, wind speed, relative humidity, total precipitation, and surface pressure. The authors recommended integrating AI-driven technology into the national meteorological system. However, they highlighted limitations related to region-specific data, the need for validation before generalisation, and the lack of substantial computational resources.

Indeed, these are essential points failing to deal with will lead to opacity in AI decision-making processes referred to as "black box", where the logic and hidden internal reasoning behind a specific decision are obscure and cannot be explained due to a lack of understanding about the hidden internal reasoning, casting a doubt about its validity. This scenario could erode the trustworthiness of AI decisions and raise ethical concerns among stakeholders and regulators, particularly in high-risk applications. Efforts are progressing to advance Explainable AI (XAI) aimed at improving AI accuracy and transparency of the reasoning behind it [27, 28]. Another key manifestation of climate change in Iraq is reduced rainfall, which has sparked interest among researchers. For example, Abdaki, M., et al. investigated Rainfall forecasting in Nineveh Governorate, northern Iraq, using deep machine learning to improve water resources management [29]. They concluded that their model could produce highly accurate results for daily rainfall forecasting and seasonal variations. One of the findings is that annual rainfall is predicted to decline at Rabbia, Haddar, Sinjar, and Mosul stations by 2030. However, Shekhan station is projected to receive a 20% increase in rainfall from 370 to 447 mm by 2030.

In another study, this time focused on southern Iraq, deep machine learning neural network (DNN) models were selected to predict rainfall, overcoming the non-linear relationship between input data and output conditions, including Unpredictable precipitation that might cause floods or droughts. The study location was the wetland area (The Marshes), located in the south of an exceptional ecosystem with vast bodies of water, inhabited by a local community dependent on the ecosystem for survival. The marshes have already lost a significant portion due to drought, leaving the arid, salty Sabkha lands devoid of life. The study's goals were to develop a rainfall forecasting model that outperforms traditional prediction models [30].

Precipitation in Iraq is also a research area of interest, as it is linked to drought and flood risks. Rainfall is a highly variable phenomenon both spatially and temporally. Bandar, Q.K.A., and Muslih, K.D. study explores Iraqi precipitation patterns using the Precipitation Concentration Index (PCI) and the Relative Seasonality Index (SI) [31]. Monthly precipitation data from 21 climate stations spanning 1940 to 2022 are utilised. The results indicate significant spatial variation in precipitation concentration across the country. Based on the PCI values, Iraq can be divided into three zones: a strongly irregular concentration in the south; an irregular precipitation concentration in the central area, and a moderate precipitation concentration in the mountainous and undulating areas.

Another consequence of climate change, due to rising temperatures and reduced rainfall, that has received attention is drought and desertification. The latter represents the last stage of land degradation. In Iraq, desertification is one of the most perilous environmental manifestations of climate change, as it directly impacts food security and human health [32, 33]. Drought had a profound impact on local communities, the economy, agriculture, and the environment [34]. Afan H. A., et al. exploited the capability offered by remote sensing platforms and deep machine learning in the prediction of the SPEI (drought index that integrates both precipitation and potential evapotranspiration to assess drought severity), to determine the impact of climate change on drought in Anbar Governorate, an arid region located in western Iraq, characterised by a harsh subtropical desert climate [35].

In another study, Alkubaisi, H., et al. investigated the effectiveness of AI techniques in enhancing the accuracy of drought forecasting models by comparing various AI tools [36]. Historical data sets related to the Standardised Precipitation Evapotranspiration Index (SPEI) near the city of Karbala, Iraq, were retrieved and used to train and test all models. On the other hand, Suliman, A.H.A., et al. evaluated the effectiveness of artificial intelligence (AI) applications across Iraq's diverse climatic zones [37]. The study utilised 47 years of historical precipitation data from 22 ground stations and two GPP datasets (Mapping Earth's Photosynthetic Pulse) from remote sensing, which quantify the total carbon sequestered by plants through photosynthesis. The authors concluded that AI tools are capable of tasks related to monitoring, managing and predicting drought.

Fartm, Z. F. A. concluded, in a detailed review of the literature, that climate change is the most significant cause of land degradation, primarily due to reduced rainfall rates and drought [38]. Other causes include urban sprawl at the expense of agricultural land, unsustainable farming methods, outdated irrigation practices, salinity, and reduced vegetation cover.

Open-source remote sensing platforms, including satellite and GIS data, are available to environmental scientists, providing a valuable data source for identifying, detecting, and monitoring desertification in Iraq [39]. Another study has focused on Mapping, assessing, and predicting desertification in the Al-Khidhir district of Al-Muthanna Governorate, in southern Iraq, through 2028. The data set, derived from remote sensing and integrated with a deep learning ANN model, has enabled the best forecasting of the spread of land degradation, which could expand to 54.1% of the land by 2028. They concluded that their study could help decision-makers develop effective control and management plans [40].

Nasir, H. N., & Hamdan, A. N. A., however, the study area encompasses the entire country of Iraq [41]. They utilised recurrent neural networks (RNNs), a type of Artificial Neural Network, to simulate weather conditions with high precision, including rain, wind, earthquakes, droughts, and temperatures. The Standardised Precipitation Index (SPI) was the model used to forecast droughts. The two scales used in this study are SPI 6, which represents short-term drought, and SPI 24, which indicates long-term drought. Data sourced from twenty-four stations selected to represent the entire study area (Iraq) with a Geographic information system (GIS). The conclusion is that Iraq has experienced mild to extreme drought at different times, and that recurrent neural networks (RNNs) would be beneficial for prediction, as they have proven effective for short- and long-term analysis with high accuracy.

2.2 Hydrology Domains

Iraq is grappling with a severe water scarcity problem combined with declining water quality as a result of interacting multiple factors that collectively left the country with a significant and steady reduction in flow of the primary water resources, the Tigris and Euphrates rivers, and a poorly prepared system to adapt to the escalating impacts of climate change [14]. Serious consequences affected public health due to the spread of waterborne diseases.

Indeed, water resources are now a global priority, which has attracted investment in introducing new technologies, including AI. Chang F.J. noted the increasing deployment of artificial intelligence techniques in hydrology to achieve effective water resource management and mitigate the effects of climate change [42]. An approach that has proven to be a powerful aid for accurately modelling complex, non-linear hydrological processes and for efficiently analysing and imaging data sources from remote sensing platforms or in situ Internet of Things (IoTs). AI-driven systems that monitor water can provide authorities with real-time information on infrastructure, consumption patterns, and water quality, which aid stakeholders in making informed decisions and developing strategies to conserve water, optimise irrigation, and implement policies to support sustainable management. AI models can detect water leaks, identify contamination hotspots, and detect illegal water withdrawals. These benefits are highly significant for Iraq, which urgently needs to monitor and manage its diminishing water resources effectively. By leveraging AI technologies, Iraq can make considerable strides toward sustainable, reliable water provision.

Assi, S., Khan, W., and Al-Jumeily, D. discuss the factors contributing to water scarcity in Iraq and propose introducing innovative, intelligent solutions that would require firm standard operating procedures and comprehensive, integrated databases [43]. The authors stressed that implementing such an innovative water system will benefit Iraq in both the short and long term, resulting in reduced pollution, improved crop and land quality, and enhanced sustainability. Communities will have better health and an improved quality of life. Indeed, if implemented, it would ensure that Iraq will progress confidently in managing the water crisis. However, significant investment is required to build a robust data infrastructure, high-powered computing and cloud storage capability.

Ahmed, Q. A., et al. attempted to assess the feasibility of AI applications for effectively managing and modelling the Tigris River as a case study [44]. Not surprisingly, the findings indicated that the main obstacles to this study are related to the availability and quality of the dataset, as well as model interpretability. However, the results showed that AI significantly enhances predictive capabilities, optimises water distribution, minimises waste, and improves flood forecasting and water quality monitoring. They concluded by emphasising the importance of improving data infrastructure and the need to fully exploit the potential of remote sensing data as a source of information on the morphologies and hydrological systems of Iraqi rivers. However, this requires validation with additional, robust, locally collected data. Allawi, M.F., et al. used AI models to predict the Monthly inflow of the Haditha Dam as another case study [45].

Groundwater, a vital component of the hydrological cycle, has attracted attention using AI tools due to its strategic position as a significant source of freshwater, renewable and replenished by rain and floods. Globally, Groundwater supplies about 25% of all water used for irrigation and half of the freshwater withdrawn for domestic purposes [46]. While Iraq is confronting declining surface water resources, groundwater has been exploited as an alternative source, often through the indiscriminate drilling of shallow wells [47]. The lack of systematic groundwater monitoring studies and the inability to accurately establish groundwater levels hinder the evaluation of its role as a long-term water supply in sustainable groundwater resource management.

Hydrology experts have increasingly applied AI techniques to groundwater forecasting, particularly crucial in Iraq, given the strategic importance of groundwater resources for agriculture and domestic use. Al-Abadi, A.M. investigated the semi-confined aquifer in Kirkuk Governorate, northern Iraq, as a case study to map groundwater potential in terms of availability [48]. The research team compared five machine learning (ML) algorithms to model the relationship between the locations of 1031 wells with specific-capacity data and nine influential groundwater occurrence factors (elevation, slope, curvature, aspect, aquifer transmissivity, specific storage, soil, geology, and groundwater depth), to map Groundwater quality for drinking was modelled using the water quality index and the weights of the chemical constituents. By combining the groundwater quality index map with the groundwater potential map via simulation, they identified three groundwater potential zones: poor, moderate, and excellent. Moreover, the study proposed a model for managing groundwater by coordinating basin-wide pumping to prevent depletion and degradation of the resource.

Mohammed, S.S. et al. investigated the impact of climate change and water scarcity on the amount and distribution of groundwater recharge in the Iraqi Western Desert groundwater system [49]. They developed an AI model to estimate soil moisture using artificial neural networks (ANN), utilising a dataset derived from geographic information systems (GIS). The results showed that approximately 455,306,884 m³ of rainwater infiltrated into groundwater during the study years, nearly half of the total estimated rainfall [50].

Muneer, A.S., et al. investigated the hydrological cycle, with a specific focus on rainfall, runoff, soil properties, and evaporation [51]. They identified that the local lack of meteorological stations as an in-situ data source would impede the prediction and calculation of surface runoff. The team utilised Artificial Neural Networks (ANNs) integrated with a geographic information system (GIS), supported by in situ field-measurement data comprising 105 soil samples from the Al-Ratba catchment area in the Iraqi western desert. They concluded that the model could predict infiltration rates without conducting manual field tests, thereby reducing costs.

Jumaah, H. J., et al. focused on detecting environmental changes in the Najaf Sea in Iraq, a lake replenished by groundwater seepage, rainfall, and occasional flow from the Euphrates River, using NDWI and GIS integrated with AI. NDWI, or Normalised Difference Water Index, developed in 1996, is a widely used remote sensing index that helps detect and monitor water bodies across landscapes, supporting water mapping, flood analysis, land-use monitoring, and environmental assessment through automated geospatial intelligence platforms [52]. AI will enable scenario modelling of water availability, such as detecting wetland and lake shrinkage, seasonal flow changes, mapping irrigation zones, and identifying waterlogging. The Najaf Sea is undergoing significant environmental changes due to climate change and urban expansion, resulting in decreasing water levels that affect the surrounding areas. The study analysed changes between 2018 and 2025, tracking variations in the water bodies and evaluating the impacts of climate change and human activity on sustainable resource management. The paper highlighted the critical role of advanced technologies in monitoring and forecasting changes in water resources. To help experts develop resilient strategies for environmental conservation and climate change mitigation.

Assessing Water quality also received interest. Al-Mukhtar M., et al., investigated water quality in Abu-Ziriq Marsh by comparing three different Artificial Intelligence (AI) techniques to predict and estimate the impact of daily flow releases from the upstream Al-Badaa regulator [53]. The data set comprises 720 records of daily water quantity data from 2017 to 2018, which the study group used to train and test the AI models. The authors suggested using AI to compute water quantity and quality parameters in the Iraqi Marshes and to inform policy decisions on water discharges to the Marshes. Such a policy is a priority given the uniqueness of Iraq's wetlands, located in the southern part of the country and representing the largest wetland ecosystem in the Middle East. It serves as an essential habitat for migratory birds and aquatic life and is home to the exceptional culture of the Marsh Arabs. Unfortunately, the ecology has been severely damaged due to decreased discharges of the Tigris and Euphrates resulting from upstream damming, conflicts, climate change, extensive drainage structures built during the 1990s, and unsustainable actions such as diverting water for irrigation, contamination from untreated industrial discharge and sewage, and contamination from the oil industry. This decline in quantity and quality led to a systematic shrinkage of the Marshlands, causing damage to the ecosystems and the livelihoods of the communities [54,55].

A crucial component of sustainable water resource management is harvesting wastewater. In Iraq, population growth, coupled with changes in lifestyles and rapid urbanisation, has unsurprisingly led to rising demands for water for domestic use and increased waste generation, posing significant threats to sustainability and public health. A situation that demands an urgent need for investment to improve the fragile domestic water distribution infrastructure, quality monitoring, and wastewater recycling. Predictably, Artificial Intelligence (AI) techniques have proven efficient in optimising wastewater treatment plant operations and reducing operational costs.

Fu G., et al. investigated the potential role of artificial intelligence (AI) in ensuring the reliability, resilience, and sustainability of urban water infrastructure (UWI) in line with the green economy's three principles (reduce, reuse, and recycle) [56]. However, as anticipated, the limited availability and low quality of training and validation data significantly impact outcomes in tasks such as monitoring consumption patterns, detecting leaks, and optimising distribution networks. Providing a robust dataset on wastewater management will enable predictive maintenance, demand forecasting, and adaptive water-pricing strategies, reduce water losses, and ensure sustainable use [57].

Zakur, Y. et al. conducted a literature review of the application of AI techniques in wastewater treatment management to enhance energy efficiency, comply with water quality regulations, and maximise recovery [58]. The author discussed how various AI algorithms can be deployed in wastewater treatment plants (WWTPs) integrated with IoT sensors to build a trustworthy dataset. In general, the AI algorithms performed better than traditional manual techniques.

Another perspective in hydrology is agriculture, which consumes roughly 70% of freshwater withdrawals in Iraq. Therefore, it is logical that water resource management should prioritise introducing measures to recycle and reduce water waste. The global trend is for significant investment in agricultural technology. The target is to achieve precision or smart agriculture through the integration of artificial intelligence with IoT to optimise resource usage, such as water, pesticides, and fertilisers. Indeed, the combination of AI, IoT, remote sensing platforms and automation is currently reshaping agriculture worldwide, offering innovative solutions to achieve sustainable outcomes.

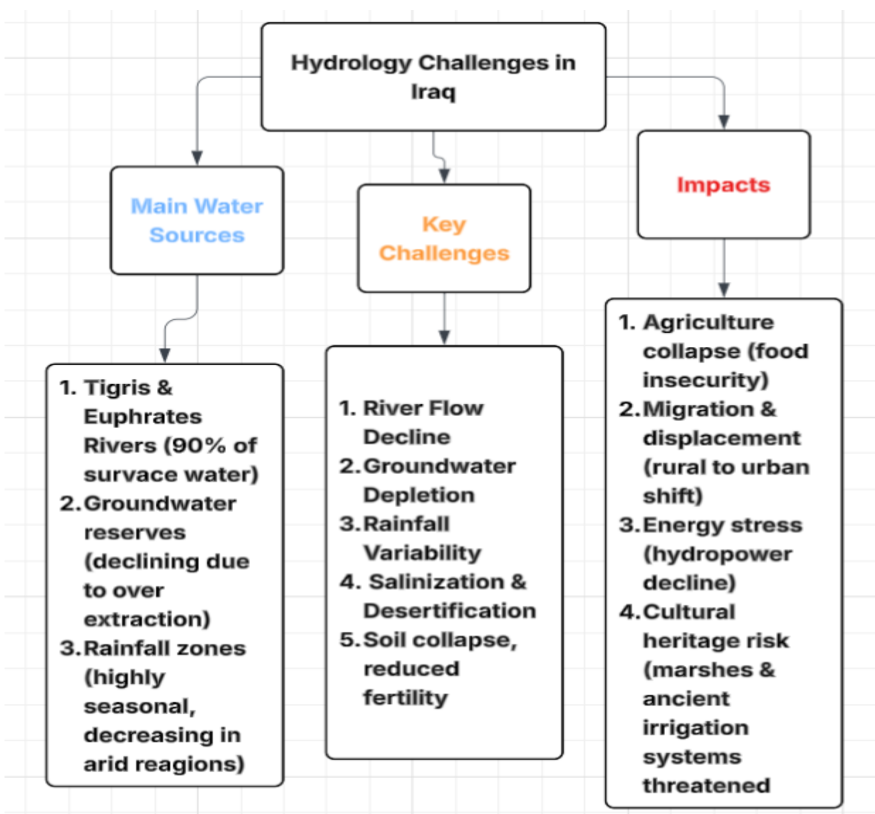
Wadi, W. I. et al. explored the reality of incorporating low-powered Internet of Things (IoT) based wireless sensors in agricultural production in Iraq to remotely monitor and study the impact of factors such as cultivated area, water resources, rainfall amounts, agrarian mechanisation, fertiliser quantities, investment and labour force, on productivity [59].

Alazzai, W.K. et al. attempted a comprehensive analysis of the transformative impact of Artificial Intelligence (AI) and the Internet of Things (IoT) in modern agriculture, revolutionising crop management and supply chain efficiency [60]. The review highlights the role of IoT in agriculture, particularly its benefits of easy installation, reduced maintenance, and lower energy demand for device sustainability [61].

However, integrating AI and IoT in agriculture presents several hurdles, including data privacy, robust infrastructure requirements, and the technological divide between developed and developing nations. Additionally, adopting these technologies requires a change in the mindset of farmers and stakeholders in the water and agriculture sectors.

A recent development is the availability of new approaches to measure soil moisture-holding capacity, an essential environmental variable [62]. Moreover, Soil temperature (ST) is an important meteorological variable which plays a significant role in the hydrological cycle and is a key parameter in agricultural management, as plant growth and soil physical processes are directly influenced by soil temperature, which controls physical, chemical, and biological reactions in soil and has a practical impact on plant growth. Different parameters, including region climate and topography, the size and structure of ground biomass and soil physical Characteristics, control the patterns of soil temperature. Al-Salihi, A. M., & Al-Ramahy, Z. A. employed an artificial intelligence technique to estimate three days ahead soil temperature at 10 and 20 cm depths by measuring Soil temperature daily for the period from January 1, 2012, to December 31, 2013, in three stations (Mosul, Baghdad, and Muthanna) in Iraq [63].

Flowchart of Iraq Hydrology Challenges



2.3 Water Pollution Domain

Globally, pollution is responsible for approximately 1.4 million deaths and nearly 1 billion illnesses worldwide, posing a significant threat to human health and the environment [64].

A significant indication of environmental deterioration in Iraq is the chemical and biological contamination of surface and groundwater, which poses considerable risks to human health and the ecosystem.

Water pollution in Iraq is a deeply rooted crisis with wide-ranging consequences for health, ecology, and national security, as evidenced by the continued exposure of the population to enteric diseases and waterborne illnesses, especially in cities like Basra and Baghdad, due to Contaminated water resulting from sewage dumping and outdated water infrastructure [65].

Worldwide, emerging modern technologies, including AI algorithms, are already being deployed for sustainable water management, offering the water sector in Iraq an opportunity to implement real-time measures to control and manage water pollution. These technologies can forecast source and pollution levels, inform stakeholders, and enable timely decision-making for effective management strategies.

Issa, M. J., et al. conducted a Trace elements analysis in sediment Tigris River samples in Wasit Governorate had proved that the sample are highly polluted with Titanium (71.9 ppm), Nickel (226.6 ppm) Chromium (425.2 ppm), Cadmium (2ppm) and Molybdenum (15.8 ppm) while the sediments were moderately polluted with Cobalt (25.1 ppm), Strontium (839.3 ppm), Copper (56.2), Manganese (106.1ppm), Vanadium (135 ppm), Niobium (9.79 ppm). However, these pollution levels are specific to that sample and cannot be generalised without validation by results from other locations on the river Tigris [66].

Rashid, M. K., et al. presented a machine learning model for identifying sources of water pollution in the Euphrates and Tigris rivers [67]. The model effectively classified water samples by pollution source and predicted impacts on water quality and the local aquatic ecosystem. The models identified hospitals, wastewater treatment facilities, upstream agricultural areas, and industrial zones, each with an associated predicted pollution density. The team collected data from multiple sources, such as aerial photographs, field surveys, and official government documents.

Abduljaleel, H. Y. investigated water-quality assessment, prediction, forecasting, and management models for the Shatt al Arab River in Basra, focusing on physical, chemical, and biochemical indicators [68]. The authors used data from a geographic information system (GIS) and the analytic hierarchy process (AHP) to identify the most polluted region in Basra. They developed a predictive model based on Recurrent Neural Networks (RNNs) to forecast TDS (Total Dissolved Solids) values at nine sites.

In a recent study, Shams, M.Y. et al. investigated the Water Quality Index and classification as indicators of water quality using several machine learning models to improve water quality prediction [69]. The results showed that deep machine learning tools outperformed other models. The importance of this study lies in its ability to predict water quality, which is crucial for mitigating and controlling water pollution.

In another study, Al-Khuzaie, M. M., et al. utilised a GIS-based artificial neural network (ANN) system to predict the Heavy Metal Pollution Index (HPI), thereby enhancing the understanding of water quality dynamics and supporting effective pollution control strategies [70]. Key findings revealed elevated concentrations of heavy metals, including arsenate, cadmium, mercury, lead, and thallium, which are toxic even in trace amounts, indicating severe pollution risks. The study proposed a more efficient and less costly approach than traditional field-observation methods to support local governments' efforts to control and manage water pollution.

Jaafer, N. S., et al. compared five artificial intelligence techniques to estimate dissolved oxygen (DO) and biochemical oxygen demand (BOD) water quality parameters [71]. The performance of each model was assessed using datasets from two different Bridges on the Tigris River in Baghdad City. The data was randomly divided into two categories: 70% for training and 30% for testing. This study has revealed that deep machine learning models are suitable for forecasting water quality indices.

AlMetwally, S. A. H., et al. study focused on exploring the feasibility of integrating Internet of Things (IoT) in real-time monitoring and controlling of domestic water quality. With deep machine learning AI models [72]. The study deployed in situ sensors to measure domestic water quality factors (acidity, alkalinity, temperature, and total suspended solids, expressed as cloudiness or haziness). Additional benefits include the system's ability to facilitate autonomous decision-making and to support real-time acquisition, transmission, processing, and storage of water quality data in a cloud-based facility, accessible remotely via a tablet or mobile application. The system empowers water consumers to manage water quality through a user-friendly interface that illustrates quality factors, in lower and upper limits and acceptable values, thereby eliminating the problematic, lengthy, and costly offline lab analysis of collected water samples. They advise that the system aligns with the smart city concept, reducing labour and operational costs.

Oil and water are emerging as a significant environmental and hydrological challenge in Iraq due to wastewater contaminated with oil from oil extraction and refineries, particularly in the southern oil fields, as wastewater from oil extraction has a high concentration of pollutants, such as metals, hydrocarbons and total dissolved solids (TDS), volatile organic compounds, bacteria, and dissolved gases. Therefore, it needs to be adequately managed and treated before it is discarded.

The predicament is that maintaining high oil and gas production requires a vast amount of fresh water, with a ratio of 1:3 barrels of fresh water per barrel of oil extracted to maintain reservoir pressure and boost oil recovery [73]. The oil industry's Water collection stations further aggravate the crisis by depriving the local population of substantial water volumes. Awadh, S. M., & Al-Mimar, a situation that demands integrated water-energy planning to avoid trade-offs between oil revenue and environmental ruin [74].

Studies on oil-produced water from oil fields and refineries have focused on meeting environmental regulations and reusing and recycling produced water. However, Alardhi, S. M., et al, attempted to predict the oil content of produced water from an Iraqi oil field [75]. The dataset was obtained from an operational plant in Iraq in June 2023, which included a variety of parameters (temperature, pressure, unit flow rate, and oil water concentration (ppm) of the feed water), which was analysed by using an artificial neural network (ANN) technology. The results showed that the ANN model was remarkably accurate and predictive in simulating water pollution, outperforming mathematical models and laboratory tests.

2.4 Air Pollution Domain

Air pollution refers to the emission of large quantities of particulates and toxic chemicals into the atmosphere, sufficient to reduce air quality and exceed national and international standards, posing a risk to human health and the ecosystem.

Kasser, M.K. conducted a literature review of air pollution across different regions of Iraq, covering the causes and types of pollutants [76]. Many studies have confirmed that exposure to chemical and biological pollutants, as well as suspended particles (PM10 and PM2.5), is associated with respiratory and cardiovascular diseases, and increases the incidence of bacterial and viral infections, as well as lung cancer, representing a significant concern in urban areas, traffic and industry-related air pollution exacerbated by climate change. Increasingly, AI models are used to analyse data from air quality sensors, weather, and traffic patterns to predict pollution levels, issue alerts to residents, and support the development of effective air quality management strategies. For example, IBM's Green Horizons project utilises AI to monitor and predict air pollution levels in cities worldwide, enabling authorities to take measures to improve air quality [77].

Jumaah, H. J., et al. applied a statistical model to predict air quality in Iraq and to determine relationships between air pollutants and the Air Quality Index (AQI), including particulate matter, for 2020 [78]. They collected data from open-source remotely sensing platforms and ground stations. The authors concluded that the results have the potential to assist responsible authorities in decision-making to manage and control vehicle-emitted air pollution in urban areas. Oday Zakariya Jasim et al 2020, study approach by integrating machine learning algorithms and a geographic information system to generate pollution prediction maps in a highly congested area in Baghdad city. The data used in this study include temperature, humidity, wind speed, wind direction, and traffic flow data (the number of light and heavy vehicles), and carbon monoxide samples collected by using mobile devises.

A significant source of air pollution in Iraq is dust storms, a climatic phenomenon caused by strong winds that transport large amounts of dust from the soil surface into the atmosphere. In 2024, they occurred over 272 days, as Iraq is in the centre of the Dust Belt, with nearly half of its total area desert. Dust storms constitute a significant source of particulate matter (PM2.5 and PM10) pollution [63, 79].

Hayawi, H., et al. used deep machine learning to develop an AI model to analyse and predict the frequency of dust storms in the three largest provinces (Baghdad, Basrah and Nineveh) until March 2027 [80]. The data included temperature, surface pressure, wind speed, wind direction, humidity, and precipitation, sourced from the Iraqi Meteorological Organisation and additional open-source data from the NASA remote sensing platform, covering the period from January 1981 to December 2022. One of the main findings is that the most critical factors in dust storms are temperature and active winds, followed by low humidity and reduced rainfall (drought). The spread of storms from one province to another depends on the time of year and the direction of the wind. The investigators tested various deep machine learning algorithms to identify the best models for predicting dust storm frequency through March 2027. They argued that their finding will support the authorities in taking necessary measures to protect and advise the public, and in developing long-term management strategies.

2.5 Biodiversity Domain

While Iraq is fortunate to have a delicate ecosystem with a unique biodiversity of animals, plants, and migratory birds, as well as freshwater and Marine life, it is becoming a casualty of climate change, water scarcity, conflicts, and the unsustainable exploitation of natural resources. Al-Al-Dabbas, M. [81].

Globally, conservation programs are already utilising AI models to monitor and manage ecosystems, track wildlife populations, identify and mitigate threats to biodiversity, and support conservation efforts. Iraq requires modern technologies to protect the unique and vulnerable ecosystems. Deep learning, a powerful subset of machine learning, could potentially emerge as a transformative technology in ecology and biodiversity research, as traditional monitoring methods are labour-intensive, costly, and limited in spatial and temporal coverage.

Salman, I. R., et al. study applies deep learning techniques to biodiversity monitoring to enhance species identification, abundance estimation, and ecosystem assessment in the Tigris River, Iraq [82]. They used a multi-tiered approach to data collection (direct field sampling, remote sensing, and citizen science) and generated a dataset of over 8,000 images across six camera locations. They considered the results evidence of AI technology's effectiveness and superiority, which could transform conservation programs, enhance aquatic biodiversity monitoring, and achieve 88% species detection accuracy. However, the main barrier was the water's extreme turbidity.

An innovative approach to biodiversity is to integrate AI with remote sensing and IoT platforms for real-time monitoring, species identification, and ecosystem management. However, as artificial intelligence continues to evolve, its role in biodiversity conservation will become even more vital aiding sustainability, accurately identifying wildlife species, reduce wildlife stress and enhance biodiversity and contribute to Sustainable Development Goals 2 (Zero hunger aiming to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture) and 15 (Life on Land to protect, restore, and promote the sustainable use of terrestrial ecosystems and safeguarding the very fabric of biodiversity that sustains human and planetary health.) to be achieved by 2030 [83].

2.6 Waste Management Sub-domain

Waste accumulation is another consequence of urbanisation, posing severe environmental and health impacts that have globally attracted innovative AI-powered waste management systems for collection, sorting, and disposal processes, including recycling and converting waste into heat and electricity. These innovative systems have transformed waste management by enabling real-time monitoring, prediction, and automation, ultimately reducing waste, optimising resource utilisation, and enhancing circular economy practices and sustainability [84].

Abdulhasan, M. J et al., in a Case Study of Nasiriyah City, South of Iraq [85], to support meeting recycling standards in innovative waste management by designing an AI system based on artificial neural networks (ANN) to sort and classify domestic waste automatically. They developed a virtual model that incorporates features extracted from images using machine learning techniques. The model was capable of analysing a dataset comprising 2,600 images of potential recyclable waste, categorised into groups. The evaluation reveals that the proposed model achieves an accuracy rate of 91.7% in classifying waste in alignment with recycling standards. However, they recognised the need for greater computational power and more data to enable the ANN to produce better results.

Olawade, D. B., et al. reviewed the benefits of Artificial Intelligence (AI) technologies in addressing the complexities of waste management systems (collection, sorting, recycling, and monitoring), particularly when integrated with the Internet of Things (IoT) [86]. However, difficulties have emerged around data quality, privacy concerns, and cost implications. The superiority of AI models over traditional systems stems from AI's capabilities in data analysis, pattern recognition, and decision-making, reshaping the waste management landscape in numerous ways.

Converting domestic waste to energy in Iraq has attracted some studies, one of which investigates the role of AI and Machine learning models to enhance effective management and sustainability [87, 88].

3. Conclusion

Globally, there is a qualified consensus that Artificial Intelligence (AI) has emerged as a transformative technology that can reshape an increasing range of sectors, such as healthcare, banking, and the environment, by fostering Reliability, resilience, and sustainability. Moreover, most studies have highlighted the limitations facing developing countries, which are still lagging in joining the digital and ICT (information and communication technologies) revolution engulfing the world. In Iraq, the assured path to success is to confidently and steadily incorporate these new technologies, including AI, IoT, and others, to close this gap and advance environmental management strategies.

Nevertheless, numerous research papers by scientists exploring AI applications across various environmental domains in Iraq have indicated a noticeable interest in deploying AI models as a real-time, effective tool superior to traditional approaches, thereby reducing human error and enhancing sustainability through improved decision-making, modelling, and prediction. The barrier, however, lies in initiating cultural change and a mindset shift among stakeholders and decision-makers, where AI and new technologies are embraced as opportunities rather than threats, and are not hindered by tokenism, bureaucracy, inadequate investment, or weak regulations.

Furthermore, from reviewed studies, there is a common thread of the need in Iraq to develop robust Infrastructure Foundations from digital connectivity (Reliable internet access and expansion of 4G/5G networks), reliable power supply (Stable grid electricity or renewable energy backup systems), AI-capable hardware, and cloud technology for data storage, processing, and analysis. This infrastructure should ensure confidence in the soundness of AI decisions and predictions, underpinned by frameworks for data privacy and sharing, ethical AI use, and appropriate legislation. The inception of Iraq's INSAI (National Strategy for AI) in 2023 is a step forward in the right direction. However, it requires adequate investment, an interdisciplinary vision, and the development of human capital in collaboration with Iraqi universities that could serve as hubs for introducing AI technology into education on a national scale. AI advancement in Iraq should be environmentally friendly through sustainable data centre management, reduced water consumption for cooling, reduced energy consumption, e-waste, and the disposal of critical non-recyclable materials. For example, a sustainable approach to electricity for data centres would consider the feasibility of integrating a renewable energy source with AI technology.

AI applications in the environmental domain in Iraq would benefit from utilising open-source data from remote sensing platforms and GIS, combined with local datasets, to confidently address Iraq's environmental priorities and ultimately be better positioned to harness the full potential of AI technology in environmental health and other sectors, avoiding "black box" problems that could undermine the confidence of the stakeholders.

Finally, all the above should be underpinned by up-to-date legal tools that ensure transparency, data protection, and cybersecurity. An updated 2009 Iraqi environmental law could act as a vehicle to support AI integration in environmental research and application. An alternative is to consider a separate legal instrument that regulates AI use across all sectors, such as health, agriculture,finance, education and others.

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