



Systems analysis for energy assets of Iraq influenced by water scarcity

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Abstract

Water security in arid and semi-arid Middle Eastern climates has been severely impacted by effects of climate change such as reduced precipitation, diminished storage, increased evapotranspiration, and prolonged heat waves. These climate effects are compounded in Iraq, where populations, agriculture, industry, and energy rely heavily on varying transboundary water flows to meet water demands. Iraq's most profitable sector, energy, is especially threatened by insufficient water supply, which complicates government decision making in energy infrastructure development. The goal of this paper is to develop a scenario-based multi-criteria analysis framework to prioritize infrastructure investments in the context of climate change and scarcity of natural resources. Infrastructure facilities are evaluated against social, economic, climate, and hydrologic criteria across a set of disruptive climatological, economic, and social scenarios to identify robust initiatives and the most and least disruptive scenarios to the system. A particular innovation of this paper is the evaluation of hydrology data derived from satellites in determining water scarcity impact on individual energy facilities. The methods are demonstrated for a critical sector of Iraq's economy: oil and natural gas. The demonstration includes 13 system-order criteria, 44 oil and gas initiatives within Iraq, and seven risk scenarios. The results include an accounting of the most and least disruptive scenarios to energy sector priorities and scenario-based system orderings to guide stakeholders in investment prioritization.

Keywords Risk management · Infrastructure resilience · Environmental security · Economic development · Systems analysis

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1 Introduction

Water scarcity in arid and semi-arid regions, such as Iraq, poses significant challenges to socioeconomic and infrastructural development. Predicting water availability in these climates requires a delicate balance of understanding natural variations, human activity, and the unpredictable perturbations introduced by climate change. Iraq's predicament is further exacerbated by its reliance on transboundary water sources, like the Tigris and Euphrates rivers, which have been increasingly subjected to upstream infrastructural developments and human activities in countries such as Turkey and Syria (Keulertz and Mohtar 2022).

As observed over recent years, diminished precipitation, intensified evapotranspiration, and prolonged heatwaves—hallmarks of a changing climate—have severely impacted water storage and availability (USAID 2017; Lootsma 2023). Moreover, anthropogenic interventions, including damming and river rerouting in neighboring countries, threaten the consistent flow of fresh water into Iraq (Price 2018; Alwash 2023). Such disruptions have already catalyzed a 40% reduction in Iraq's river levels over the past two decades (International Energy Agency 2019; Lootsma 2023). By 2035, forecasts suggest a water supply–demand gap approaching 11 billion cubic meters, underscoring a dire need for strategic water management (The World Bank Group 2022).

Despite significant advancements in climate and hydrological forecasting capabilities, a discernible gap persists in integrating these data with the broader socioeconomic and institutional landscapes. While current models excel in predicting natural phenomena, they often fall short when tasked with weaving in infrastructure development and maintenance, economic systems, and institutional dynamics—particularly for shared resource pools such as transboundary water systems (Linkov and Trump 2019). Although we can predict the fluctuations in precipitation or changes in river flow, understanding how these changes reverberate through societal structures, economies, and governance frameworks remains challenging. The absence of such integrated frameworks leaves a gap in our ability to predict and respond to the broader consequences of environmental changes on human systems (Merad and Trump 2020). This includes identifying and executing the necessary steps to withstand and absorb climate and infrastructure stressors, as well as positioning societies residing in at-risk watersheds to recover from and adapt to disruptive events like extended droughts.

Given the intertwined relationship between water availability, economic development, and infrastructure

operations, there is a critical need for a systems-oriented analytical framework (Linkov et al. 2022). Such a framework should account for a multitude of scenarios—from natural disasters and climate shifts to economic stressors—that could further stress the water-energy nexus. Iraq's sizable energy sector, particularly the oil and natural gas industry, exemplifies such a nested dependency. With the potential risk of water insufficiency threatening energy production, investment decisions in this sector must be discounted to accommodate intermediate and long-term water scarcity.

To address that challenge, this paper utilizes a scenario-based multi-criteria analysis model to prioritize infrastructure investments within the broader context of climate change and natural resource scarcity. A particular innovation of this paper is the evaluation of hydrology data in determining water scarcity impact on individual energy facilities. The methods are applied to the case of Iraq, which has a range of competing objectives for economic development and societal wellbeing against a backdrop of potential future water scarcity from the Tigris-Euphrates watershed. Where previous studies have focused climate risk analysis on the study of climate scenarios, we further incorporate climate and hydrological features as system success criteria and indicate assets where risk and resilience interventions would yield the greatest return on national interest. Through a blend of these climate and hydrological criteria with social and economic criteria, we aim to establish a comprehensive investment prioritization roadmap for resilient systems.

2 Background

The United Nations (UN) has identified water scarcity as a global endemic fed by compounding effects of local water stressors and the broader effects of climate change on water volume and quality (United Nations and UNESCO 2023). Frequent extreme weather events and natural disasters, coupled with continuing temperature rises, will further stress the water resources, food and energy security, and infrastructure of vulnerable regions into the future (Alwash et al. 2018; USAID 2022). Communities, such as Iraq, relying on shared and transboundary water resources additionally face potential water conflicts as water consumption and demands increase (USAID 2017; United Nations and UNESCO 2023). In 2022, Iraq was identified as the fifth-most vulnerable country to water, climate, and environmental insecurity (International Organization for Migration 2022).

Iraq was rich in water resources until the 1970s. However, the destruction and degradation of

infrastructure, desertification of previously fertile lands, freshwater salinization, and increases in co-riparian water usage have depleted Iraq's water supply (Al-Ansari et al. 2015). Iraq relies on transboundary water sources for nearly all its freshwater supply, leaving the nation vulnerable to upstream water use and dam construction and storage (Al-Ansari et al. 2015). Completion of Turkey's Southeastern Anatolia Project (commonly referred to by its Turkish acronym, GAP), which will include the construction of 22 dams and 19 hydraulic power plants, is estimated to result in a 70% reduction in transboundary river flows of the Euphrates River (Price 2018). The Euphrates River has already seen significant declines in flows, with levels having decreased by over 40% from pre-2000 levels (Alwash et al. 2018). These water supply challenges coincide with a rising population and the resulting increases in residential, agricultural, and industrial water consumption (Alwash et al. 2018).

Water usage in Iraq is heavily concentrated in three sectors: agriculture, residential, and energy/industry. Agriculture—a crucial sector for ensuring domestic food security—accounts for an estimated 85% of total water withdrawals (Alwash et al. 2018). Recent investments in the sector have focused on modern irrigation practices with hopes to increase agricultural water efficiency (Alwash 2023). In the residential water sector, only about three quarters of the urban areas, and less than half of the rural areas, receive municipal water supply (Alwash et al. 2018). In periods of drought, many residents are subject to water quotas, limiting household water access to just a few hours daily (Iraq: WASH Severity Classification 2021). Per capita water consumption in Iraq is nearly double that of international averages, driven by low water tariffs resulting in wasteful residential usage and a lack of citizen awareness of the extent of water scarcity concerns (Alwash et al. 2018; Ward et al. 2022). The energy sector, particularly the production of oil and natural gas, is similarly demanding on Iraq's water supply (Yousif et al. 2022). Iraq's water requirements for oil production are approximately 1.5 barrels of water per barrel of oil, on the high end of the 1.3 to 1.5 barrels global average (International Energy Agency 2019).

Ensuring water security in Iraq in the face of climate change of variability of water supply and demand requires sector-specific resilience planning to limit disruption to infrastructure and services (The World Bank Group 2022). In 2021, Iraq's Ministry of Water Resources highlighted the need for prioritization and sustainable development of infrastructure projects for water-engaged sectors, including oil and energy production. With environmental and climate risks threatening natural resource availability, ensuring water, food, and energy security requires methods for connecting natural resource data to industrial and

infrastructural decision making (United Nations and UNESCO 2023).

3 Methods

3.1 Scenario-based multi-criteria decision analysis

When considering infrastructure development decisions in a resource-constrained environment, decision makers must consider multiple, often competing, factors when evaluating candidate assets for investment—affordability, sustainability, carbon mitigation, social equity, and more (Thorisson et al. 2017). Further, evaluation and quantification of the risk to development priorities of changing future conditions are a critical component of robust decision making (Hamilton et al. 2013).

Effective decision analytic techniques combine risk analysis, modeling tools, and stakeholder viewpoints to evaluate the performance of alternatives against criteria (Palma-Oliveira et al. 2018; Linkov et al. 2020). This paper applies theory from multi-criteria decision analysis (MCDA) and scenario analysis to establish infrastructure development priorities and quantify the disruption of climate and other downstream scenarios to those priorities. MCDA is an established framework in systems analysis and decision making which synthesizes data and the value set of the stakeholder to prioritize amongst a set of potential decisions (Linkov et al. 2020). In general, MCDA begins with the gathering of the set of alternatives or possible decisions, the set of criteria by which alternatives will be evaluated and compared, and criteria weights representing the relative importance of each criterion to the stakeholders. Alternatives are scored against each criterion and scaled by criteria weights. These scores define a prioritization of alternatives and provide an easily interpretable decision-making roadmap for stakeholders of all backgrounds (Hassler et al. 2020; Jenkins and Keisler 2022; Lambert et al. 2022).

MCDA provides valuable insights into system priorities for current conditions; however, as a standalone framework, it can fail to account for the risk of future stressors' shuffling of system priorities (Linkov et al. 2012). By introducing scenario-based methods, we can evaluate risk to an infrastructure system as the influence of scenarios on priorities (Karvetski et al. 2011; Lambert et al. 2013; Thorisson et al. 2017; Thorisson and Lambert 2021). In evaluating risk to infrastructure development in regions vulnerable to climate change effects, stakeholders must consider how climate change, and the cascading social, economic, technological, and political conditions, disrupt development priorities. Extending MCDA with scenario analysis allows for consideration of scenario-specific

criteria and weights to define scenario-specific system priority orders (Schroeder and Lambert 2011). This scenario-based MCDA framework delivers a risk-informed analysis which evaluates how disruptive scenarios impact a system order, thereby identifying robust decision alternatives and determining the most and least disruptive scenarios to system priorities (Hassler et al. 2020).

Scenario-based MCDA methods are broadly applicable across industries and have been used in enterprise risk analysis to evaluate emerging technological and health stressors in correctional facilities (Andrews et al. 2023), cybersecurity investments (Moghadasi et al. 2022), emerging technologies (Trump et al. 2020), public health intervention strategies (Talantaev et al. 2022), green energy investment strategies for energy services firms (Jenkins and Keisler 2022), and early initiatives for biofuel development (Connelly et al. 2015). Bonato et al. (2022) used scenario-based MCDA to evaluate informational and physical flood resilience measures in Venice. They assessed the risk management and resilience initiatives against community critical functions across four scenarios developed from expert climate projections. They noted the crucial step of considering multiple-hazard scenarios due to the unpredictable nature of event co-occurrence, a step which this paper adopts in the case study presented later in this paper. Karvetski et al. (2011) considered physical infrastructure investment portfolios to increase coastal community resilience to rising sea levels. They constructed scenarios from conditions related to global sea-level rise forecasts, population shifts, extreme temperatures, wear and tear, and changes in fossil fuel reliance. Lambert et al. (2012) focused scenario-based MCDA methods on major infrastructure projects in a volatile region of Afghanistan. Decision alternatives were grouped into high-level projects, including energy and electricity development initiatives, and were scored for drought and other political and social scenarios. Projects were classified by their baseline ranking as high, medium, or low, and by their threat level, indicated by a significant decrease in scenario ranking relative to baseline.

While Bonato et al. (2022), Karvetski et al. (2011), and Lambert et al. (2012) consider climate change forecasts in their development of *scenarios* impacting infrastructure systems, they do not account for recent climate trends in their evaluation of alternatives against system *criteria* such as sustainability and natural resource availability. Analysis of these climate trends for each alternative enhances scenario-based MCDA methods as governments and agencies place a heightened focus on climate resilient infrastructure planning.

3.2 Hydrological monitoring and analysis

This paper advances previous methods of scenario-based MCDA by including hydrology and climate data not only for development of risk scenarios, but as a metric for evaluation and prioritization of resilient infrastructure investments. These data are incorporated into the model as system-order criteria and used to evaluate candidates for infrastructure investment alongside other social, political, and economic criteria.

The transboundary nature of Iraq's water supply presents unique challenges to the collection and analysis of water resource data. In many regions, field-collected data may be missing, incomplete, or inaccessible. It may be difficult for stakeholders to obtain a holistic water resources picture and predict future water supply (Voss et al. 2013). However, modern remote-sensing techniques for hydrological data collection, including satellite imaging, are unconstrained by political boundaries and provide the necessary spatial and temporal resolution for hydrological analysis (Duan et al. 2021). Many of these datasets, including those referenced in this study, are publicly available and fill data gaps in regions where field data are either not collected or not shared (Albarakat et al. 2022). In cases where in-situ data are available alongside satellite data, additional calibration steps can be taken to reduce bias (Waheed et al. 2020); these steps are outside the scope of this study.

Several recent remote sensing hydrology case studies have focused specifically on Iraq and surrounding regions due to the unique need for transboundary monitoring. Albarakat et al. (2022) used satellite imagery to monitor drought and surface reservoir area in three transboundary river basins of Iraq—Mosul, Qadisiyah, and Dukan—over four timescales varying in length. Their findings confirmed the capability of satellite imagery to effectively observe drought events, and they suggested the use of longer timescales for transboundary region drought monitoring. Ethaib et al. (2022) performed a change detection analysis using satellite images in the Thi-Qar governorate which identified dramatic decreases in marshlands surface water. Studies have upheld the accuracy and quality of NASA satellite data for these regions. Albarakat and Lakshmi (2019) evaluated vegetative cover and health of the Mesopotamian marshes post-2002 with data from three NASA sensors varying in spatial and temporal resolution. They found consistent trends and high correlation across the three datasets, including NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) which we utilize in this paper. Amini et al. (2023) compared NASA Global Land Data Assimilation System (GLDAS) soil moisture data with ground-collected observations in the dry Kermanshah province of Iran. They verified through statistical measures that the GLDAS soil moisture estimation

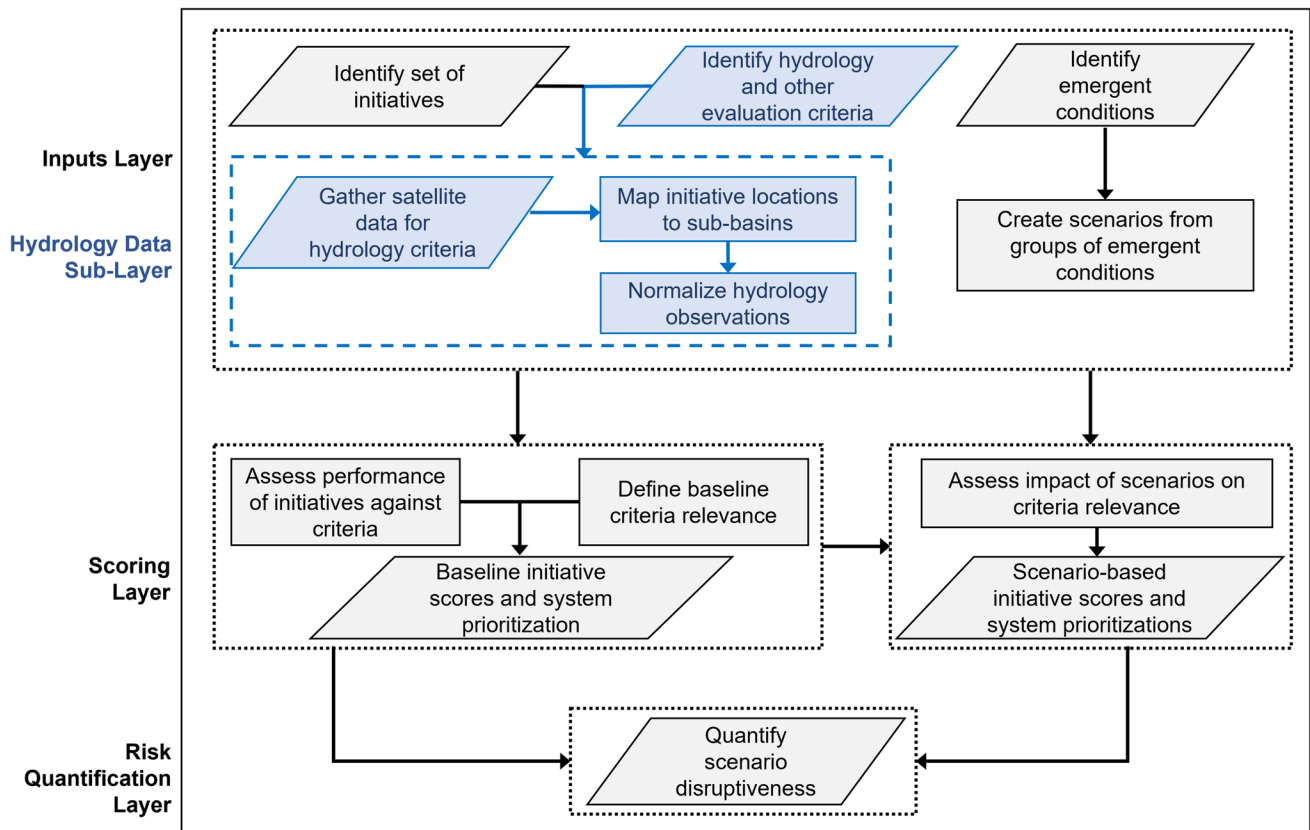


Fig. 1 Workflow diagram for a systems analysis of climate change and water scarcity disruptions to infrastructure priorities. The hydrology data sub-layer introduces hydrology metrics as inputs for risk analysis of an infrastructure system

aligned with the ground-collected observations, and thus, GLDAS was an appropriate measure for the region.

These studies support the suitability of remote sensing data collection for hydrological analysis of domestic and transboundary basins in Iraq. In this paper, normalized difference vegetation index (NDVI) is developed from the MODIS dataset, and air temperature and soil moisture are gathered from the GLDAS dataset. In addition, precipitation data are sourced from NASA’s Integrated Multi-satellitE Retrievals for GPM (IMERG) dataset. The specific use and analysis of satellite hydrology observations in this study are outlined in detail in Sect. 3.3.1.

3.3 Risk register evaluation

This paper aims to close the gap between traditional methods for climate-informed risk and decision analysis and modern methods for hydrologic and climate scenario analysis. The risk register tool introduced by this paper synthesizes qualitative stakeholder criteria and quantitative hydrological observations to assist decision makers in infrastructure development decisions. The methodology is adapted from Hassler et al. (2020) and Loose et al. (2022) and is extended

by the incorporation of hydrologic criteria and data analysis. Figure 1 outlines the methods in a workflow diagram. First, the core model inputs of criteria, initiatives, emergent conditions, and scenarios are gathered. We then outline the methods for scoring initiatives against criteria across a set of scenarios. The baseline system order and scenario-based system orders are compared to identify the most and least disruptive scenarios to infrastructure investment priorities, as well as the most robust individual initiatives.

The risk register tool is built upon four sets: criteria, initiatives, emergent conditions, and scenarios. We first define the set of criteria, $C = \{c_1, c_2, \dots, c_m\}$, which represent stakeholder goals or values. These criteria can be sourced from stakeholders and literature reviews. This paper extends previous definitions of criteria by including hydrological metrics to represent hydrological health and level of water security in the location of a particular initiative. These hydrologic criteria are explained in further detail in Sect. 3.3.1. The set of initiatives, $X = \{x_1, x_2, \dots, x_n\}$, includes the assets, projects, technologies, or policies being considered for selection, investment, or prioritization. Initiatives are identified through stakeholder interviews and agency reports. The set of emergent conditions,

$E = \{e_1, e_2, \dots, e_q\}$, is defined as future events, policies, or conditions which may affect the value of initiatives within the system. These conditions are sourced from stakeholders, historical events, and current trends. Scenarios, $S = \{s_1, s_2, \dots, s_r\}$, are developed by grouping one or more emergent conditions into the most critical higher-level threats to the system. Each scenario is a subset of E .

After defining the sets of criteria, initiatives, and scenarios, we establish methods for scoring initiatives against criteria. These scores are calculated for a baseline and each scenario, establishing a system ranking or order of initiatives for each scenario. The baseline system order serves as the comparison point for evaluating the disruptiveness level of the various scenarios.

In consultation with stakeholders and analysts, each criterion c_j is assigned a baseline weight, w_{jb} , reflecting its relative importance or value to system stakeholders in the baseline scenario. Next, we assess how the relevance (and thus, weights) of each criterion changes in the case of each scenario. For each scenario, the criteria are determined to either *increase* in relevance, *increase slightly*, *decrease slightly*, *decrease*, or have *no change*. This incremental change determination, as opposed to a complete re-weighting, simplifies the process for stakeholders who often carry intuitive judgements about how system goals evolve in changing conditions (Karvetzki et al. 2011). These changes in relevance scale the baseline weights up or down, defining new scenario-specific weights, w_{jk} , for each criterion c_j and scenario s_k .

Having defined the baseline and scenario-specific criteria weights, we next assess the relationship between the criteria and the initiatives. This assessment is completed by considering how well each initiative achieves each criterion—*very well*, *well*, *somewhat*, or *none*. The four assessment levels correspond to numerical scores, x_{ij} , the numerical score of initiative x_i for criterion c_j . For the more subjective criteria, the criteria-initiative assessment level is determined by stakeholder and expert perspectives in combination with agency reports and supporting data. Data-based criteria (e.g., hydrology criteria) are assigned their assessment level based on the observed data. The criteria-initiative assessment process for hydrological criteria is discussed in detail in Sect. 3.3.1.

Initiative scores are calculated for each scenario (the baseline and all disruptive scenarios) by computing the criteria-weighted sum of scores, as shown in Eq. 1. The score for an initiative x_i and scenario s_k is denoted as $V(x_i)_k$.

$$V(x_i)_k = \sum_{j=1}^m w_{jk}x_{ij}, \forall i \in X, \forall k \in S \tag{1}$$

The system order or ranking of initiatives for scenario s_k is determined by Eq. 2, where \succ indicates a higher position

in the order. The ranking of an initiative x_i (a number from 1 to n) in scenario s_k is denoted as $R(x_i)_k$.

$$V(x_i)_k > V(x_j)_k \Rightarrow x_i \succ x_j, \forall i, j \in X \tag{2}$$

Finally, a scenario disruptiveness score is calculated for each scenario. The disruptiveness score for a scenario s_k , $D(s_k)$, is calculated by a sum of squared differences method as shown in Eq. 3, where $R(x_i)_b$ is the ranking of initiative x_i in the baseline scenario and $R(x_i)_k$ is the ranking of initiative x_i for scenario s_k . The disruptiveness score can also be normalized for ease of comparison.

$$D(s_k) = \sum_{i=1}^n (R(x_i)_b - R(x_i)_k)^2 \tag{3}$$

The methods outlined above can be an iterative process amongst analysts and stakeholder groups. Stakeholders can be divided into groups based on job function or experience to account for the different values and goals held by each group. Criteria, initiatives, and emergent conditions can be reassessed over time and updated to reflect resulting changes in system prioritization and scenario disruptiveness.

3.3.1 Hydrologic data and criteria scoring

The introduction of hydrologic metrics as evaluation criteria requires methods for connecting individual infrastructure facilities or assets to hydrologic datasets. This study utilizes the HydroBASINS¹ dataset of the World Wildlife Fund to map initiatives to the hydrological sub-basin in which they are located (Lehner and Grill 2013). HydroBASINS are available at 12 levels of spatial resolution. The Level 05 (L05) granularity was chosen for this analysis to provide a sub governorate-level evaluation of hydrological features while ensuring a large enough sub-basin area with adequate data coverage. Iraq fully or partially contains 31 L05 sub-basins, with an average sub-basin area of 27,564 km². Figure 2 shows the four major river basins and the L05 hydrological sub-basins of Iraq. Eighteen sub-basins cross political boundaries and provide valuable insight into the transboundary rivers supplying most of Iraq’s water supply. The initiatives and L05 sub-basins are added to a layered ArcGIS map for visualization and mapping. Sub-basins may not be unique to one initiative; some sub-basins may contain multiple initiatives. Some initiatives, such as oil pipelines, major roadways, or nationwide policies, can cross through or apply to multiple sub-basins. Additional analysis or communication with stakeholders may be required to determine appropriate methods for hydrological analysis of these initiatives.

¹ See <https://www.hydrosheds.org/products/hydrobasins> for additional information on the HydroBASINS dataset.

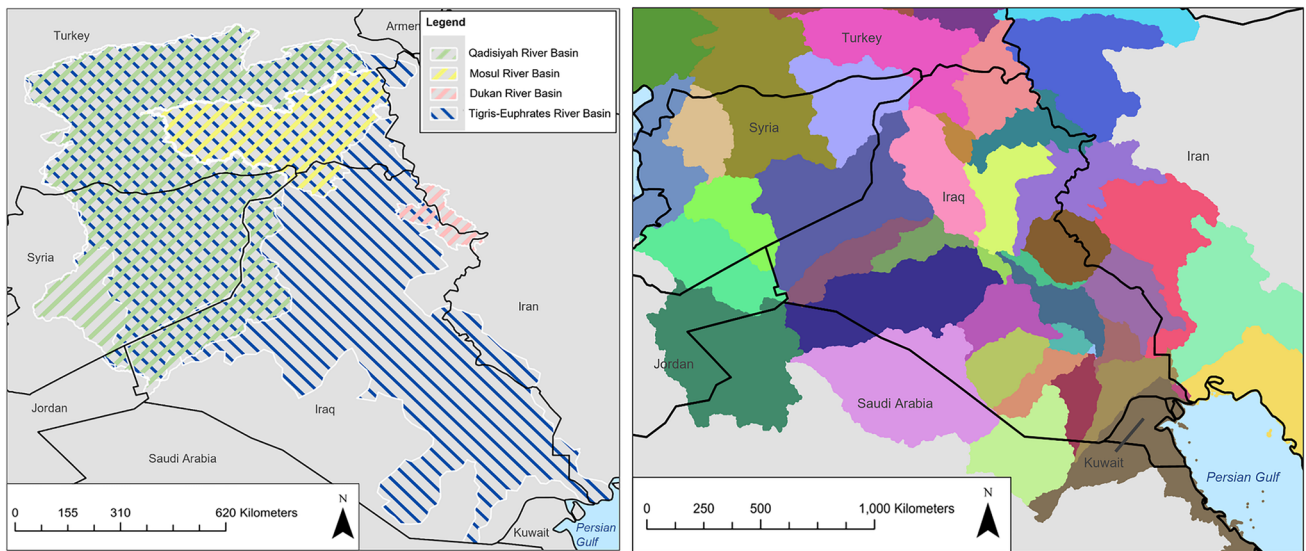


Fig. 2 The four major transboundary river basins of Iraq (left); the domestic and transboundary L05 HydroBASINS of Iraq (right) (generated in ArcGIS)

Table 1 Hydrology metrics used in ordering energy assets

Metric	Measurement units	Spatial resolution	Temporal resolution	Satellite/sensor/model
Average annual precipitation	mm	0.1° × 0.1°	1 Month	NASA IMERG
Average annual RZSM	m ³ /m ³	0.25° × 0.25°	1 Month	NASA GLDAS
Average annual air temperature	°C	0.25° × 0.25°	1 Month	NASA GLDAS
Average annual NDVI	0–1 Index	250m × 250m	16 Days	NASA MODIS
Minimum monthly precipitation (December–April, only)		0.1° × 0.1°	1 Month	NASA IMERG

We consider the previous 5 years of available data (2018–2022) for analysis. The timeframe is limited to the most recent 5-year period to accurately reflect the recent hydrological conditions in Iraq and avoid data skew from earlier observations which do not necessarily reflect current climate and hydrological realities of the region. An annual time series for the previous 20 years (2003–2022) confirmed that the 2018–2022 period was suitably representative of historical trends and was neither significantly wetter nor significantly drier than other periods. Future studies may extend or otherwise alter the timeframe of analysis according to study goals and data availability. Five hydrology metrics, collected from NASA satellite datasets as described in Table 1, are studied. These five metrics were chosen for their ability to assess the natural water supply from precipitation in a sub-basin, as well as the impacts of water supply and water usage on soil moisture and vegetative health. Observations for the five metrics are gathered and averaged across each of the L05 sub-basins. Four of the metrics, annual precipitation, annual root zone soil moisture (RZSM), annual air temperature, and annual NDVI are recorded as the average of

the individual annual averages within the 2018–2022 study period. The final metric, minimum monthly precipitation, records the precipitation level of the month within the study period (restricted to the rainy months of December through April) with the lowest precipitation. This metric captures a previous 5-year worst case month during Iraq’s rainy season (Ethaib et al. 2022). Each initiative is assigned the metric values of the L05 sub-basin in which it is located.

To compare hydrological observations across the set of initiatives being studied, a normalized metric index (NMI) between 0 and 100 is calculated for each initiative and metric. Equation 4 shows the calculation of the NMI for the annual precipitation metric for an initiative x_i , where AP_i is the 2018–2022 average of annual average precipitation for initiative x_i and X is the set of initiatives.

$$NMI_i^{AP} = 100 \times \frac{AP_i - \min\{AP_j\}_{j=1}^n}{\max\{AP_k\}_{k=1}^n - \min\{AP_j\}_{j=1}^n}, \forall i \in X. \quad (4)$$

The NMI formulas for RZSM, NDVI, and minimum monthly precipitation follow the structure of Eq. 4 for

each respective dataset. The NMI formula is constructed such that initiatives located in basins with higher observed values have higher NMI, and initiatives located in basins with lower observed values have lower NMI. For the air temperature metric, a slight variation is made to Eq. 4 to reflect that higher observed values for this metric reflect a negative climate feature. Equation 5 shows the calculation of the NMI for the air temperature metric for an initiative x_i , where AT_i is the 2018–2022 average of average annual air temperature for initiative x_i and X is the set of initiatives.

$$NMI_i^{AT} = 100 \times \frac{\max\{AT_j\}_{j=1}^n - AT_i}{\max\{AT_j\}_{j=1}^n - \min\{AT_k\}_{k=1}^n}, \forall i \in X \quad (5)$$

In the case of air temperature only, initiatives located in basins with *lower* observed air temperatures have higher NMI, and initiatives located in basins with *higher* air temperatures have lower NMI.

For each of the five metrics, initiatives are classified into one of four bins based on the value of their NMI. Bins are constructed as follows: bin 1 = [0, 25), bin 2 = [25, 50), bin 3 = [50, 75), bin 4 = [75, 100]. These bins represent the relative hydrological health of the initiatives. For example, an initiative whose NMI values fall in bin 4 for all five metrics would be considered to have healthier hydrological features than an initiative whose NMI values fall in bin 2 for all five metrics. These bins inform the criteria-initiative assessment as described in Sect. 4 and shown in Tables 6 and 7, with bin 1 assessed as *none*, bin 2 assessed as *somewhat*, bin 3 assessed as *well*, and bin 4 assessed as *very well*. In other words, initiatives with NMI values in bin 4 are considered to perform *very well* (in risk register terminology) against hydrological criteria.

4 Case study

This case study demonstrates the methods on a set of 44 oil and natural gas initiatives within Iraq, establishing a system prioritization order and evaluating the disruptiveness of several water supply, climate, and other scenarios. Iraq is the second-largest OPEC producer of crude oil, and oil exports contribute over 90% of total government revenues (U.S. Energy Information Administration 2022). As decarbonization efforts in the energy sector gain traction across the world, renewable energy projects in Iraq have thus far been limited in their success by the high construction and maintenance costs, interference from high air temperatures and dust pollution, and gaps in renewable energy policy (Mohammed et al. 2023). Thus, in the short- and medium-term, oil production

and revenues remain a priority for maintaining energy stability and providing funds for government investment in both the oil and non-oil economic sectors (The World Bank 2022; The World Bank 2023). A 2019 International Energy Agency report projected Iraq's oil production to increase by approximately 1.2 million barrels per day (mb/d) by 2030 (International Energy Agency 2019). However, achieving these production levels will require an additional 3 mb/d of an already scarce water supply for oil extraction practices (Conca and Weinthal 2018; International Energy Agency 2019).

The oil recovery, refining, and transport sub-sectors are all in need of physical infrastructure improvements and expansion. Many oil refineries and pipelines were damaged or functionally destroyed during the conflicts with ISIS from 2014 to 2017. Iraq's largest refinery, in Baiji, lost nearly half of its production capacity after an attack in 2014 and, as of 2021, still operates well below its pre-2014 production levels (U.S. Energy Information Administration 2021). Security concerns and outdated production and transportation infrastructure continue to hinder Iraq's oil production and energy supply (AL-Saadi et al. 2022).

Non-oil energy and electric production in Iraq comes mostly from natural gas (Ersoy and Terrapon-Pfaff 2022); however, development of natural gas infrastructure has lagged behind that of oil (U.S. Energy Information Administration 2021). Most of Iraq's natural gas is associated, meaning the gas is a byproduct of oil production. The lack of infrastructure to capture, treat, and transport this associated natural gas has led to high levels of flaring, with Iraq only behind Russia in terms of flared gas volumes (International Trade Administration 2021; U.S. Energy Information Administration 2021; The World Bank Group 2022). In 2018, over half of the natural gas produced in Iraq was flared, forfeiting US\$2.5 billion in potential revenues and a potential 10 gigawatts of much needed electricity (The World Bank Group 2022). The World Bank identified the elimination of gas flaring and the development of the necessary treatment infrastructure as an urgent, "no regret" adaptation measure (The World Bank Group 2022). Investments in natural gas capture and treatment could also provide much needed economic and energy diversification, with oil markets threatened by global shifts towards lower carbon energy production (International Trade Administration 2021; The World Bank Group 2022).

To prioritize energy infrastructure assets in Iraq, we consider a set of eight non-hydrologic criteria collected from stakeholders and agency reports and five hydrologic criteria collected from NASA satellite-based datasets. Table 2 presents the 13 system-order criteria, $\{c_1, c_2, \dots, c_{13}\}$ and their respective baseline relevance level. These criteria are developed in collaboration with agency experts and decision-makers, and include environmental sustainability,

Table 2 Criteria relevance for the baseline scenario evaluating energy resource priorities

Criterion	Baseline relevance
c.01—Sustainability	Medium
c.02—Social equity	Medium
c.03—Adaptability	Medium
c.04—Mitigation	Medium
c.05—Manage transitions	High
c.06—Affordability	Medium
c.07—Harm reduction	High
c.08—Economic development	Medium
c.09—Annual precipitation	Low
c.10—Soil moisture	Low
c.11—Air temperature	Low
c.12—Vegetative cover	Low
c.13—Monthly low precipitation	Low

progress towards decarbonization through adaptation and mitigation, affordability of initiatives, and five measures of hydrological health. Stakeholders and agency experts classify baseline relevance levels of criteria as *low*, *medium*, or *high*. These relevance levels each correspond to a numerical criteria weight—1 for criteria with *low* relevance, 2 for criteria with *medium* relevance, and 4 for criteria with *high* relevance. The five hydrology criteria are given *low* baseline relevance to reflect a baseline system prioritization with minimal consideration to hydrological health. The set of initiatives, $\{x_1, x_2, \dots, x_{44}\}$, is comprised of oil refineries, oil and gas fields, pipelines, and natural gas projects in varying stages of development. The initiative locations are shown in Fig. 3, and initiatives are listed by name in Table 3.

Emergent conditions, $\{e_1, e_2, \dots, e_{22}\}$, are gathered from historical and recent trends and include natural disasters, hydrological trends and projections, population changes, technological changes, and changes in political cooperation

Fig. 3 The 44 energy initiative locations included in the systems analysis (generated in ArcGIS)

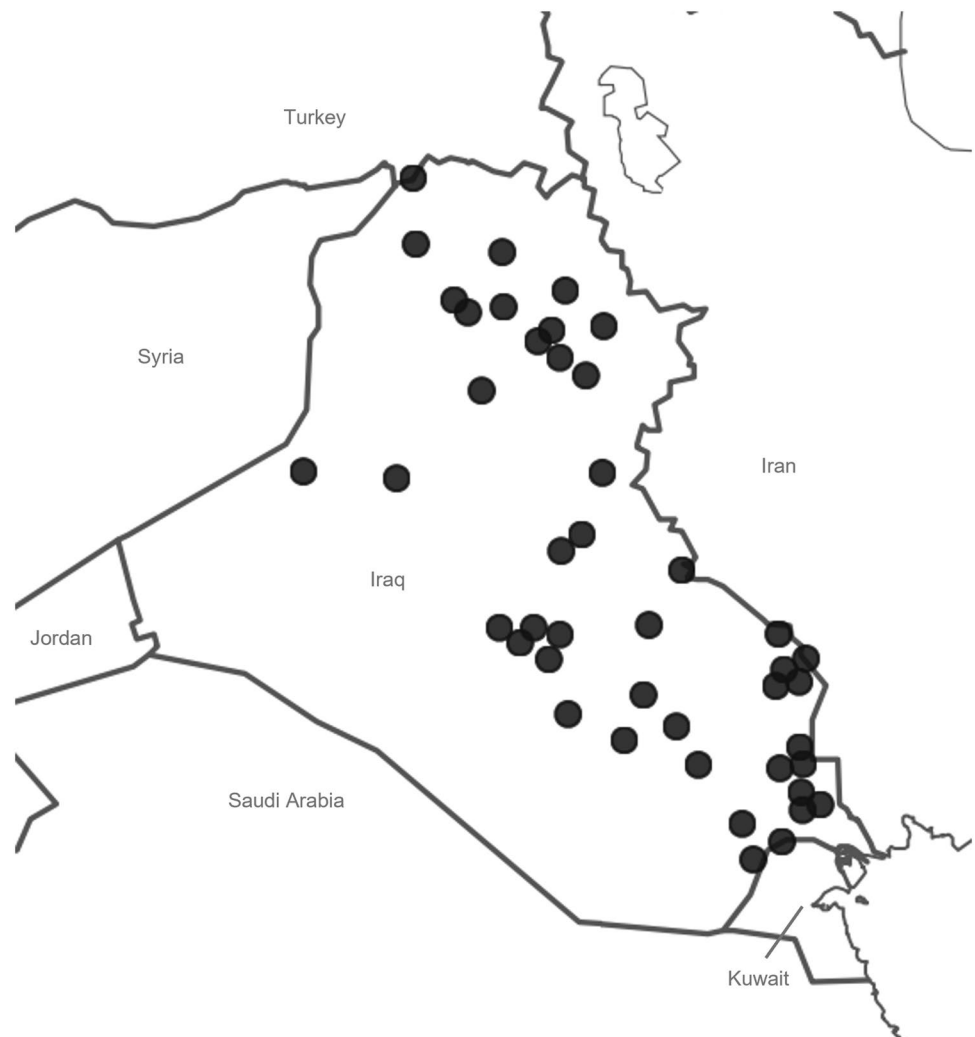


Table 3 Energy infrastructure initiatives evaluated for environmental and water scarcity risk analysis

Index	Initiative	Source
x.01	Baiji Refinery (North Refineries Company)	EIA 2021
x.02	Kirkuk Refinery (North Refineries Company)	EIA 2021
x.03	Sininya Refinery (North Refineries Company)	EIA 2021
x.04	Hadeetha Refinery (North Refineries Company)	EIA 2021
x.05	Qayara Refinery (North Refineries Company)	EIA 2021
x.06	Kasak Refinery (North Refineries Company)	EIA 2021
x.07	Daura Refinery (Midland Refineries Company)	EIA 2021
x.08	Najaf Refinery (Midland Refineries Company)	EIA 2021
x.09	Samawah Refinery (Midland Refineries Company)	EIA 2021
x.10	Diwaniya Refinery (Midland Refineries Company)	EIA 2021
x.11	Karbala Refinery (Midland Refineries Company)	EIA 2021
x.12	Basra/Shuaiba Refinery (South Refineries Company)	EIA 2021
x.13	Missan Refinery (South Refineries Company)	EIA 2021
x.14	Nassiriya Refinery (South Refineries Company)	EIA 2021
x.15	Iraq section of Iraq to Turkey (IT) pipeline	EIA 2021
x.16	Turkey section of Iraq to Turkey (IT) pipeline	EIA 2021
x.17	Kirkuk-Banias/Tripoli Pipeline	EIA 2021
x.18	Strategic pipeline (Kirkuk to Persian Gulf)	EIA 2021
x.19	Iraq pipeline to Saudi Arabia (IPSA)	EIA 2021
x.20	Rumaila Oil Field	GEM 2023
x.21	West qurna Oil Field	GEM 2023
x.22	Halfaya Oil Field	GEM 2023
x.23	Kirkuk Oil Field	GEM 2023
x.24	Nassiriya Oil Field	GEM 2023
x.25	East Baghdad oil field (in development)	GEM 2023
x.26	Zubair Oil Field	GEM 2023
x.27	Al-Fakkah Oil Field	GEM 2023
x.28	Nahr Umr Oil Field	GEM 2023
x.29	West Qurna 2 Oil Field	GEM 2023
x.30	Majnoon Oil Field	GEM 2023
x.31	Abu Gharb Oil Field	GEM 2023
x.32	Bai Hassan Oil Field	GEM 2023
x.33	Bazerkan Oil Field	GEM 2023
x.34	Al Gharaf Oil Field	GEM 2023
x.35	Jambur Oil Field	GEM 2023
x.36	Subba Oil Field	GEM 2023
x.37	Ratawi Oil Field	Offshore Technology (2023)
x.38	Akkas Natural Gas Project (nonassociated)	EIA 2022
x.39	Mansuriya Natural Gas Project (nonassociated)	EIA 2022
x.40	TotalEnergies Gas Growth Integrated Project (Natural Gas)	EIA 2022
x.41	CNPC Natural Gas Treatment Halfaya	EIA 2022
x.42	South Gas Co/Baker Hughes Natural Gas Treatment Nassiriya/Gharaf	EIA 2022
x.43	Basra Gas Company Flared Gas Reductions	IFC 2019
x.44	Basra Gas Company LNG Plant	IFC 2019

EIA energy information administration, *GEM* global energy monitor (2023), *IFC* international finance corporation (2019)

Table 4 Emergent environmental, hydrological, and other conditions considered to evaluate energy sector risk

Index	Emergent condition
e.01	Dust storm
e.02	Desertification
e.03	Increase in annual precipitation
e.04	Decrease in annual precipitation
e.05	Increase in soil moisture
e.06	Decrease in soil moisture
e.07	Increase in air temperature
e.08	Increase in vegetative cover
e.09	Decrease in vegetative cover
e.10	Increase in dam building/storage upstream
e.11	Reduction in international cooperation
e.12	Decrease in total labor productivity
e.13	Lack of infrastructure
e.14	Change to water tariffs
e.15	New technology
e.16	Lapse in support for old technology
e.17	Water pollution
e.18	Widespread disease/healthcare crisis
e.19	Population increase
e.20	Population decrease
e.21	Decrease in oil price
e.22	Global shift away from fossil fuels

Table 5 Climate and other scenarios which disrupt energy sector priorities

Index	Scenario
s.01	Decrease in transboundary inflows
s.02	Drought and desertification
s.03	Drought + decrease in transboundary inflow
s.04	Prolonged heatwave
s.05	Increase in agricultural water use
s.06	Population and health crisis
s.07	Decrease in oil price/demand

(Table 4). Seven scenarios, $\{s_1, s_2, \dots, s_7\}$, are formed from the set of emergent conditions (Table 5). The scenarios represent the critical climate, water security, and cascading threats impacting oil and gas infrastructure. The set of scenarios includes three water scarcity scenarios (*s.01—Decrease in transboundary inflows*, *s.02—Drought and desertification*, *s.03—Drought + decrease in transboundary inflows*) one other climate scenario (*s.04—Prolonged heatwave*), two domestic scenarios (*s.05—Increase in agricultural water usage*, *s.06—Population and health crisis*), and one economic scenario (*s.07—Decrease in oil price/demand*). The scenario *s.03—Drought + decrease in*

transboundary inflows represents the combined effects of concurrent realizations of *s.01* and *s.02*.

When faced with environmental, economic, and other stressors, agencies’ and decision-makers’ priorities may shift (Miller et al. 2023). To reflect these changes, a qualitative assessment is performed on the set of criteria for each scenario. Each criterion is assessed to *increase*, *increase slightly*, remain *neutral*, *decrease slightly*, or *decrease* in relevance in the case of each of the seven disruptive scenarios outlined. This change in criteria relevance corresponds to a scenario multiplier on the baseline criteria weight. For example, criterion *c.09—Annual Precipitation Level* has low baseline relevance and receives a baseline criteria weight of 1. Because the criterion *increases* in relevance during scenario *s.02—Drought and desertification*, the criterion weight is multiplied by 6 to define the scenario-specific criteria weight for this criteria-scenario pair, $1 \times 6 = 6$. Criteria which *decrease slightly* or *decrease* in relevance for scenarios receive fractional scenario multipliers between 0 and 1, effectively decreasing the scenario-specific criteria weights.

Next, the criteria-initiative assessment is performed by determining how well each initiative achieves the goal represented by each criterion. This assessment is performed in Tables 6 and 7, where (●) represents *very well*, (◐) represents *well*, (◑) represents *somewhat*, and a blank entry represents *none*. Each of the four scoring levels correspond to a numerical score, with *very well* corresponding to the highest score (1) and *none* corresponding to the lowest score (0). For the eight non-hydrologic criteria, this assessment is completed with the knowledge of stakeholders, industry experts, and agency reports. For the five hydrologic criteria, this assessment is completed by calculating the NMI bin (1, 2, 3, or 4) for each initiative-criterion pair and following the bin-assessment mapping defined in Sect. 3.3.1. For example, if an initiative falls in NMI bin 4 for hydrologic criterion *c.10—Soil Moisture Level*, it will receive the rating of *very well* (●) for that criterion in the assessment. The criteria-initiative assessment scores recorded in this step are then weighted by the baseline and scenario-specific criteria weights to define initiative scores for the baseline and seven disruptive scenarios. The initiatives are ranked by their scores, from highest to lowest, to establish the system orders for each scenario.

5 Results and analysis

Figure 4 presents the results of the case study. The figure shows the baseline ordering of the 44 oil and gas initiatives (ordered from top to bottom on the left side of the figure) as well as how each initiative rises or falls in the scenario-disrupted system order. The initiatives are ordered for the

Table 6 Baseline assessment of energy initiatives' (x.01 through x.22) achievement of system-order criteria, where (●) represents very well, (◐) represents well, (○) represents somewhat, and a blank entry represents none

	c.01— Sustainability	c.02— Social equity	c.03— Adaptability	c.04— Mitigation	c.05— Manage transitions	c.06— Affordability	c.07— Harm reduction	c.08— Economic development	c.09— Annual precipitation	c.10— Soil moisture	c.11—Air temperature	c.12— Vegetative cover	c.13— Monthly low precipitation
x.01— Bajji Refinery	○					○		●	○	◐	○	◐	○
x.02— Kirkuk Refinery	○					○		●	○	◐	○	◐	○
x.03— Sininya Refinery	○					○		○	○	◐	○	◐	○
x.04— Hadeetha Refinery	○					○		○		●	○		
x.05— Qayara Refinery	○					○		○	◐	◐	○	◐	○
x.06— Kasak Refinery	○					○		○	●	○	●	●	
x.07— Daura Refinery	○					○		●	○	◐	○	◐	○
x.08— Najaf Refinery	○					○		◐			◐		
x.09— Samawah Refinery	○					○		◐					
x.10— Diwaniya Refinery	○					○		○					
x.11— Karbala Refinery	○					○		●				◐	
x.12— Basra/ Shuaiba Refinery	○					○		●					

Table 6 (continued)

	c.01— Sustainability	c.02— Social equity	c.03— Adaptability	c.04— Mitigation	c.05— Manage transitions	c.06— Affordability	c.07— Harm reduction	c.08— Economic development	c.09— Annual precipitation	c.10— Soil moisture	c.11—Air temperature	c.12— Vegetative cover	c.13— Monthly low precipitation
x.13— Missan Refinery					○			●	●	●		○	
x.14— Nassiriya Refinery					○			●		●		○	
x.15—Iraq section of Iraq to Turkey (IT) pipeline								○	○	●	○	●	○
x.16— Turkey section of Iraq to Turkey (IT) pipeline								●	○	●	○	●	○
x.17— Kirkuk- Baniyas/ Tripoli Pipeline								○	○	○	○	○	○
x.18— Strategic pipeline (Kirkuk to Persian Gulf)					○			●					
x.19—Iraq pipeline to Saudi Arabia (IPSA)								●					
x.20— Rumaila Oil Field			○					●					

Table 6 (continued)

	c.01— Sustainability	c.02— Social equity	c.03— Adaptability	c.04— Mitigation	c.05— Manage transitions	c.06— Affordability	c.07— Harm reduction	c.08— Economic development	c.09— Annual precipitation	c.10— Soil moisture	c.11—Air temperature	c.12— Vegetative cover	c.13— Monthly low precipitation
x.21— West Qurna Oil Field			○	○	○	○		●					
x.22— Halfaya Oil Field			○	○	○	○		●	●	●		○	

baseline and disruptive scenarios according to Eq. 2. The black bar represents the baseline ranking of each initiative (1 to 44). The blue bar represents the highest that an initiative rises in the prioritization order under a disruptive scenario. The red bar represents the lowest that an initiative falls in the system prioritization under a disruptive scenario. If an initiative does not rise (similarly, fall) in ranking under any scenario, no blue (similarly, red) bar is shown. The position of the baseline initiative ranking (black bar) for an initiative gives general guidance on the initiative’s robustness. If the baseline ranking is near the center of the full bar for an initiative, then the initiative’s position within the system priority order is inconsistent across scenarios; it rises and falls with similar magnitude across different scenarios (for example, *x.01—Baiji Refinery*). If the baseline ranking is near the left of the full bar with a longer red segment, then the initiative has greater potential to fall in ranking when disruptive scenarios occur (for example, *x.35—Jambur Oil Field*). Likewise, if the baseline ranking is near the right of the full bar with a longer blue segment, then the initiative has greater potential to rise in ranking when disruptive scenarios occur (for example, *x.15—Iraq section of Iraq to Turkey (IT) pipeline*).

The most robust initiatives are those which are highly ranked in the baseline and disruptive scenarios, or those which may have a slightly lower baseline ranking but rise significantly in ranking in the case of scenario disruption. For example, *x.41—CNPC Natural Gas Treatment Halfaya* is ranked highest overall in the baseline scenario, with *x.42—South Gas Co/Baker Hughes Natural Gas Treatment Nassiriya/Gharaf* ranked second. In all seven disruptive scenarios, these two associated natural gas initiatives remain ranked in the top two, in either order. In fact, the top seven ranked initiatives in the baseline scenario are all natural gas initiatives; the top five are all associated natural gas initiatives, and the sixth and seventh ranked initiatives are the two nonassociated natural gas initiatives included in the study. The natural gas initiatives are quite robust, with only one of these initiatives ever falling outside the top 10 initiatives under scenario disruption. This result aligns with stakeholder expectations that initiatives contributing to reductions in natural gas flaring would be high priorities for investment due to their ability to both decrease harmful emissions (achieving sustainability and mitigation criteria) and diversify the energy supply for domestic use and export (achieving social equity, manage transitions, and economic criteria). The robustness of these initiatives indicates that they are strong candidates for investment and represent lower-risk investments considering the future scenarios studied in this case.

All oil pipeline initiatives are ranked in the bottom half of the baseline ordering; however, these initiatives tend to rise into the top half of the prioritization order under disruption.

Table 7 Baseline assessment of energy initiatives' (x.23 through x.44) achievement of system-order criteria, where (●) represents very well, (◐) represents well, (○) represents somewhat, and a blank entry represents none

	c.01—Sustainability	c.02—Social equity	c.03—Adaptability	c.04—Mitigation	c.05—Manage transitions	c.06—Affordability	c.07—Harm reduction	c.08—Economic development	c.09—Annual precipitation	c.10—Soil moisture	c.11—Air temperature	c.12—Vegetative cover	c.13—Monthly low precipitation
x.23—Kirkuk Oil Field			○	○	○	○	○	●	○	●	○	●	○
x.24—Nassiriya Oil Field			○	○	○	○	○	○		●		○	
x.25—East Baghdad Oil Field (in development)								●	○	●	○	○	
x.26—Zubair Oil Field			○	○	○	○	○	●		●		○	
x.27—Al-Fakkah Oil Field							○	○	●	●		○	
x.28—Nahr Umr Oil Field			○	○	○	○	○	○					
x.29—West Qurna 2 Oil Field			○	○	○	○	○	●	○	●		●	
x.30—Majnoon Oil Field			○	○	○	○	○	●					
x.31—Abu Gharb Oil Field							○	○	●	●		○	
x.32—Bai Hassan Oil Field			○	○	○	○	○	○	●	○	●	●	●
x.33—Bazerkhan Oil Field							○	○	●	●		○	
x.34—Al Gharaf Oil Field							○	○		○		●	
x.35—Jambur Oil Field			○	○	○	○	○	○	○	●	○	●	○
x.36—Subba Oil Field			○	○	○	○	○	○	○	○		○	
x.37—Ratawi Oil Field							○	○					
x.38—Akkas Natural Gas Project (nonassociated)			●	●	●		○	○		●	○		
x.39—Mansuriya Natural Gas Project (nonassociated)			●	●	●		○	○	○	○	○	●	○

Table 7 (continued)

	c.01—Sustainability	c.02—Social equity	c.03—Adaptability	c.04—Mitigation	c.05—Manage transitions	c.06—Affordability	c.07—Harm reduction	c.08—Economic development	c.09—Annual precipitation	c.10—Soil moisture	c.11—Air temperature	c.12—Vegetative cover	c.13—Monthly low precipitation
x.40—TotalEnergies Gas Growth Integrated Project (Natural Gas)	○	○	●	●	●	●	●	●	●	●			
x.41—CNPC Natural Gas Treatment Halfaya	○	○	●	●	●	●	●	●	●	●		○	
x.42—South Gas Co/Baker Hughes Natural Gas Treatment Nassiriya/Gharaf	○	○	●	●	●	●	●	●	●	●		○	
x.43—Basra Gas Company Flared Gas Reductions	○	○	●	●	●	●	●	●					
x.44—Basra Gas Company LNG Plant	○	○	●	●	●	●	●	●					

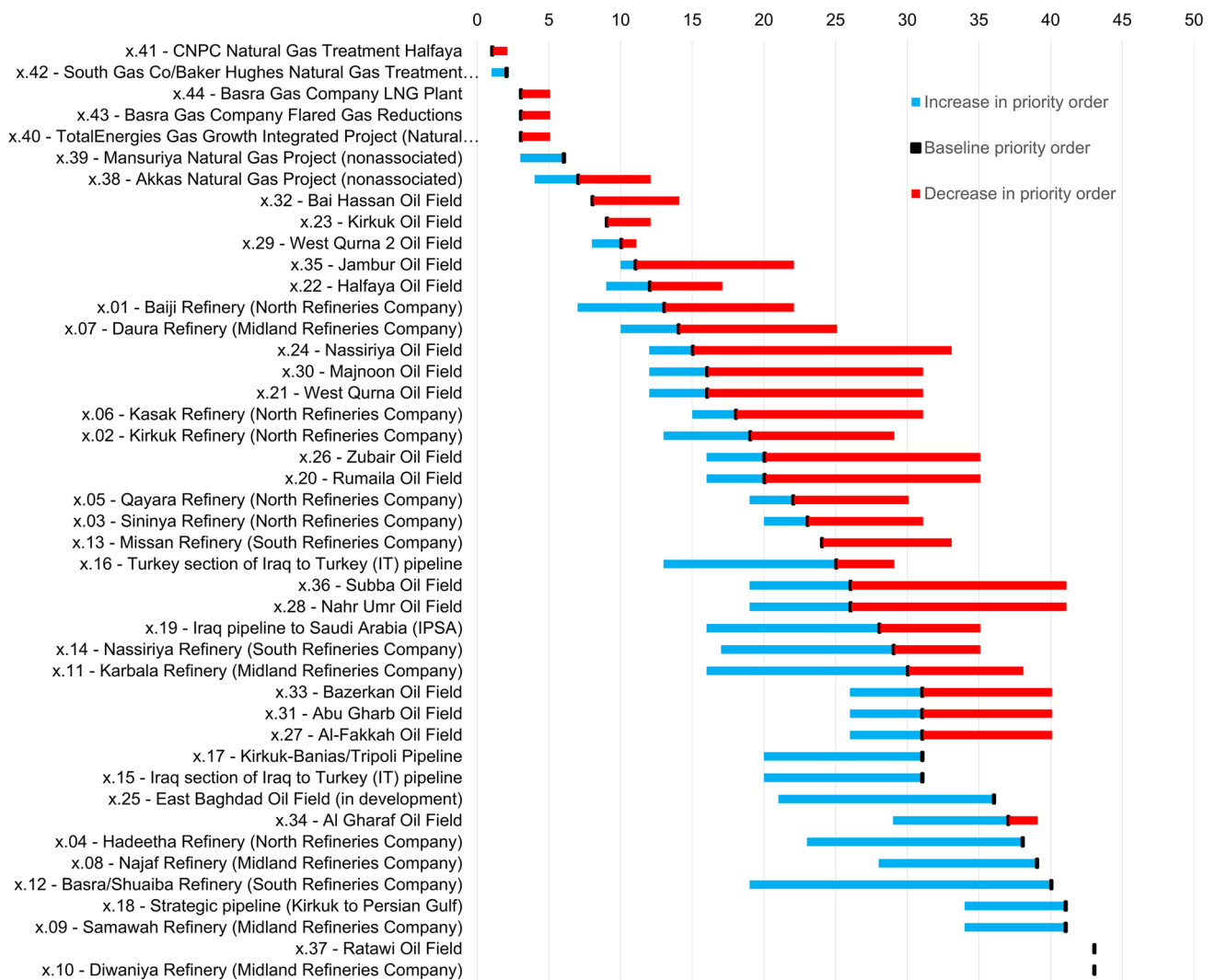


Fig. 4 Energy asset investment prioritization for baseline and disruptive scenarios

Of note is *x.19—Iraq pipeline to Saudi Arabia (IPSA)* which has not operated in Iraq since the early 2000s. Further examination shows that the initiative rises from 28 to 16th in priority order for scenario *s.07—Decrease in oil price/demand*. The Saudi Arabian section of the pipeline has been used for transporting natural gas to power plants domestically, and adapting the Iraqi portion of the pipeline for natural gas transport could offer an economic boost through diversification of energy export (U.S. Energy Information Administration 2021). The major operational oil pipeline in Iraq, the Iraq–Turkey pipeline, rises significantly in priority for all scenarios except *s.07—Decrease in oil price/demand*. Almost all oil field initiatives tend to fall in ranking under scenario disruption, except for *x.29—West Qurna 2 Oil Field*, which can rise from 10th to seventh under disruption, while only potentially falling one position to 11th. The large capacity of recoverable reserves in the field

gives it significant economic influence. The South Refineries Company’s *x.12—Basra/Shuaiba Refinery*, located in the populous southern city of Basra, is ranked 40th in the baseline order but can rise to 19th under the *s.06—Population and health crisis* scenario. In these times of increased water stress, additional investment in the refinery becomes a priority to maintain production and economic levels. The two lowest ranked initiatives in the baseline, *x.10—Diwaniya Refinery* and *x.37—Ratawi Oil Field*, remain the lowest ranked initiatives across all scenarios, indicating that these initiatives are poor candidates for investment.

These results serve as investment recommendations for government and agency planners wishing to incorporate climate and hydrological effects on water supply into their planning and decision-making processes. The most robust initiatives, in this case, natural gas processing facilities, represent strong candidates for investment as they continue

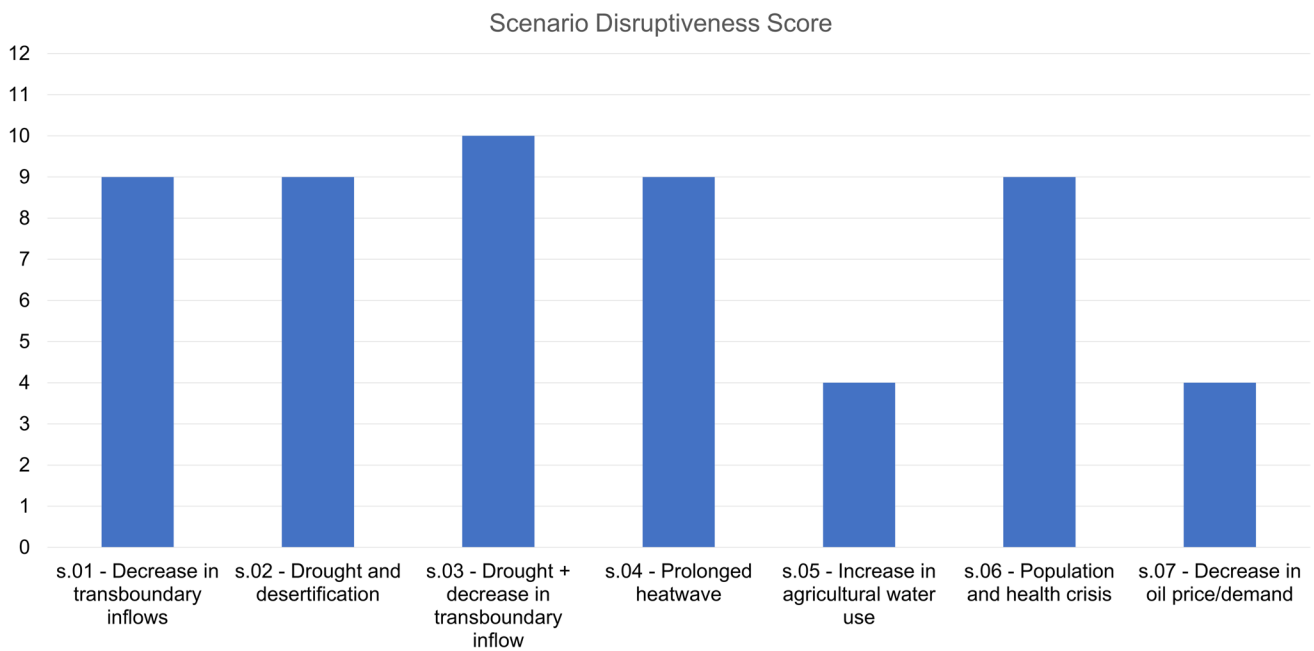


Fig. 5 Scenario disruptiveness scores for climate, domestic, social, and economic scenarios

to outperform other initiatives against evaluation criteria across all the scenarios studied. Initiatives with low baseline rankings, or those at risk of steep drop in priority under climate change scenarios, may not be good candidates for investment. Initiatives falling in the middle of the baseline prioritization order, or those which can rise and fall equally for the studied scenarios, should be considered for further analysis in the case that resources remain after prioritizing investment in the most robust scenarios.

Understanding the extent to which an infrastructure system is disrupted by environmental, economic, and other scenarios allows agencies to make more risk-informed investment decisions (Bostick et al. 2018). To that end, Fig. 5 shows the disruptiveness scores of each scenario, normalized out of 100. Five of the seven scenarios, *s.01—Decrease in transboundary inflow*, *s.02—Drought and desertification*, *s.03—Drought + decrease in transboundary inflow*, *s.04—Prolonged heatwave*, and *s.06—Population and health crisis*, result in relatively even disruption to oil and gas system priorities as evidenced by the similarity of their normalized scores. Notably, however, the disruptiveness scores for these five scenarios range between nine and 12, reflecting low levels of disruption on the normalized scale. This indicates that the energy infrastructure priorities are not, in general, significantly rearranged

by these scenarios. The two least disruptive scenarios, *s.05—Increase in agricultural water use* and *s.07—Decrease in oil price/demand* could each result in an overall decrease in oil and natural gas production. While a decrease in production levels would certainly impact the productivity of individual oil and gas initiatives, it follows that an overall production decrease may not greatly affect the prioritization order of individual facilities; the highest priority facilities would remain high priorities, albeit at lower levels of production or economic potential relative to the baseline levels.

6 Discussion

The methods introduced in this paper prioritize the robustness of decision alternatives; that is, alternatives which remain top priorities across a set of scenarios are considered strong candidates for investment. Decision makers may also consider other measures, such as minimax regret, depending on the properties and constraints of the system being analyzed. Measures of financial value may also be considered to generate a priority ranking in terms of loss, cost, revenues, cost-efficiency, or risk–benefit ratio. These financial measurement approaches were not used in the

current case because monetization was not possible across the diversity of projects.

This paper measures risk as the disruption of priorities induced by scenarios (Karvetzki et al. 2011; Lambert et al. 2013; Thorisson et al. 2017; Hassler et al. 2020; Thorisson and Lambert 2021; Loose et al. 2022). Scenarios identified as most disruptive may become candidates for further probabilistic analysis of alternative risk metrics such as likelihood and consequence (Kaplan and Garrick 1981).

While the demonstration presented in this paper focuses on the oil and gas sector of Iraq, government and agency stakeholders must also consider the trade-offs associated with investment in any particular sector. Additional case studies evaluating transportation infrastructure, water treatment facilities, and regional and local development projects will present new sets of initiatives, scenarios, and system goals. With limited natural and financial resources available, robust decision-making across these many critical sectors will require decision-makers and policymakers to consider competing perspectives and trade-offs in pursuit of their larger goals.

7 Conclusions

This paper has demonstrated methods for integrating hydrological data into scenario-based multi-criteria decision analysis to evaluate climate and water scarcity risks for infrastructure systems. The methods connect risk analysis, decision analysis, and satellite remote sensing techniques in a comprehensive model. The model was applied to a case study of 44 oil and natural gas initiatives in Iraq to provide a risk-informed infrastructure prioritization accounting for potential future climate conditions.

The results identified natural gas processing facilities, especially associated gas projects, as the most robust infrastructure investments. These facilities ranked highest across all scenarios studied and represent lower-risk options amidst uncertain future climate conditions. In contrast, certain oil refineries and fields emerged as risky, lower-priority options based on their inferior performance against evaluation criteria across scenarios.

In terms of disruptiveness, climate-related scenarios like drought and heatwaves posed the greatest disruption to infrastructure priorities. However, the normalized disruptiveness scores indicated the overall system priorities were not extensively shuffled even by the most disruptive scenarios. This suggests the proposed model provides a robust prioritization able to withstand variability in climate futures.

This research makes three key contributions. First, it advances previous methods by incorporating hydrological observations as both system criteria and scenarios, allowing decision-makers to assess alternatives against both current

and future hydrological scenarios. Second, it provides a broadly applicable framework combining risk, decision, and climate analysis for infrastructure planning. Third, it delivers actionable results to guide investment in Iraq's critical energy sector. Future work will expand the methods across sectors, assets, and regions within Iraq. Additional perspectives from different stakeholder groups will also be explored. The methods introduced in this paper have worldwide implications for any agency or government evaluating infrastructure investments vulnerable to climate change. This study provides a valuable roadmap for connecting climate data to risk-informed decision making.

The methods presented enable more resilient and sustainable infrastructure planning amidst uncertainty. By evaluating facilities against social, economic, and crucially, hydrological criteria across an array of potential futures, investment priorities emerge which are robust despite disruptive events. The integrated analysis empowers stakeholders to make forward-looking, climate-conscious decisions which build system resilience and ensure continued services vital to societal and economic functions.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Megan C. Marcellin, Gigi Pavur, Davis C. Loose, and Benjamin D. Trump. The first draft of the manuscript was written by Megan C. Marcellin and Benjamin D. Trump. Megan C. Marcellin, Gigi Pavur, Saddam Q. Waheed, and Benjamin D. Trump revised and edited previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Competing interests Authors Igor Linkov and James H. Lambert are editors-in-chief of Environment Systems and Decisions, and author Benjamin D. Trump is a member of the editorial board. These authors have not participated in deciding the suitability of this manuscript, assigning reviewers, or rendering decisions on this manuscript. The authors have no other relevant financial or non-financial interests to disclose.

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