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Integrated Approaches to Water Resource Management in Anbar Province, Iraq: Strategies for Addressing Scarcity and Enhancing Agricultural Sustainability

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ABSTRACT

The critical challenge of addressing water scarcity in Anbar Province, Iraq, necessitates the adoption of integrated water resource management strategies to meet the escalating demand for water. This study evaluates the potential of three scenarios over a 30-year period (2010–2040) to mitigate water shortages and enhance agricultural sustainability. Data were collected through site visits and extensive reviews of literature pertaining to water resource integration. The Water Evaluation and Planning (WEAP) model, combined with Geographic Information Systems (GIS), was employed to simulate and analyse the scenarios. The baseline scenario relied exclusively on surface water resources, representing current conditions. The second scenario introduced treated wastewater for irrigation alongside surface water, while the third scenario incorporated groundwater resources in addition to surface water. Results indicated that the second and third scenarios could reduce unmet water demand by 36% and 84%, respectively, by 2040 when compared to the baseline. These findings underscore the effectiveness of integrating treated wastewater and groundwater resources to alleviate water shortages and support sustainable irrigation practices. Based on the analysis, it is recommended that a combined approach involving surface water, groundwater, and treated wastewater be implemented to ensure the sustainable management of water resources in Anbar Province. Such integration is anticipated to address water scarcity while enhancing agricultural productivity and long-term resilience to resource constraints in Iraq.

1. INTRODUCTION

Iraq faces a critical challenge in addressing its growing water demands, a problem projected to intensify in the coming years due to various environmental and anthropogenic factors [1]. Climate change has significantly exacerbated this issue, with rising temperatures, increased evaporation rates, and irregular rainfall patterns contributing to water shortages. These challenges are particularly severe in the agricultural and domestic sectors, which are under increasing pressure due to rapid population growth and the consequent expansion of agricultural activities [2].

The situation has been further aggravated by upstream countries, where the construction of dams and reservoirs has led to significant reductions in the flow of water into Iraq. This reduction in water availability underscores the urgent need for a comprehensive and strategic vision for water management. Such a vision must include the development and implementation of advanced irrigation techniques, the reduction of water losses, and the utilisation of non-conventional water resources, alongside ongoing research to optimise water management practices [3].

To address these challenges, this study evaluates the impact of integrating various water resource strategies on meeting regional water demands. Previous research has provided valuable insights into similar issues. For instance, a study conducted in Kano State examined the factors affecting water supply and demand through the analysis of statistical water data. The findings revealed that the inability to meet water demand was primarily due to inadequate water management strategies [4].

2. LITERATURE REVIEW

Based on the scrutinized literature, apparent was that many researchers attacked such problems numerically. Among them, for example, were the following:

- WEAP was applied to Algeria, as it is confronted by a significant deficit in precipitation, which significantly affected water resources quality as well as quantity [5].
- WEAP was tooled to evaluate so as plan Nablus so as Tulkarm catchments, where the results designated that the treated wastewater will be 16×10^6 m^3 by 2035 [6].
- WEAP was implemented in Marahoué Basin in Côte d' Ivoire to put forward a water planning strategy for the

agricultural, domestic, and the industrial sectors. The results designated that the sectors were arranged in a descending order (i.e. agricultural, domestic and then industrial sector) with demands of 91.7, 39.5, and 1.9 $\times 10^6$ m^3 [7].

Water resources management has a direct influence of the water sustainability through conducting measures to establish functional use of resources and economic promotion [8].

- WEAP was applied in Iraq in Al-Anbar Province, where 2 scenarios were simulated. The reference scenario considered imposing tax on water, where the results designated that the 2nd scenario provided 179 × 10^6 m^3 [9].
- WEAP was implemented to attain an integrated water resource management system for the Dhasan River Basin in India, where 5 scenarios were simulated to predict future demand. The results indicated that by year 2050, population growth rate will increase, and industrial and agricultural progress will impose an increased demand, which will impose environmental threats. Accordingly, implementing a serious irrigation technique that promotes agricultural practices is a necessity [10].
- WEAP was utilized to evaluate the water sustainability as well as its consumption under the future demand in the Euphrates region, where the results indicated an increment of 297 × 10^6 m^3 by 2035 [11].
- WEAP was applied to Egypt to assess the water demand by replicating 3 scenarios, where the results designated that a water shortage of 26 × 10^6 m^3 is evident by 2025. This emphasized the development of planning strategies alternatives for utilizing canals, specifying timing of ground irrigation, removal of aquatic weeds in waterways and eliminating sugarcane areas in old agricultural lands. However, alternatives were proposed for groundwater pumping rates, as well as sprinkler and drip irrigation systems in the field [12].
- WEAP was tooled in Anbar Province for water assessment and planning, where a reference scenario was considered and treated water reuse was investigated. The results designated that the 2nd scenario will save 317.70 $\times 10^6$ m^3, if water resources management plans are utilized in this area [13].

It is essential to take in consideration the quality of the surface and subsurface water within different areas, likewise assessing the seasonal variation of several factors such pH, DO, BOD, TDS [14]. Accordingly, several studies were achieved to map the spatial distribution of precipitation and groundwater reservoirs. Additionally, many researchers were involved in detecting the regional flow trends of groundwater as well as the capability of utilizing it [15]. Among them, for example, were the following:

- A survey was carried out to manage the water resources in the Western Desert, where the results designated that the renewable and non-renewable groundwater encompasses 30 $\times 10^6$ m^3 [16].
- WEAP was employed to manage groundwater in the 'Zeuss Koutine' aquifer in Tunisia, where a decision support system was developed to evaluate the hydraulic system and the water management scenarios up to 2030 [17].
- WEAP was tooled to simulate and assess surface runoff as well as groundwater under climate change conditions in the Mahabad region of Iran, where the results designated a decrement in the surface runoff and a decrement in groundwater. Accordingly, it was recommended to put forward strategies to reduce the impact of climate change [18].
- Geographical Information System "GIS" was utilized to determine the groundwater recharge areas and the possibility of acquiring them. This was achieved due to a precipitation shortage [19].
- WEAP was utilized to promote groundwater efficiency in Qazvin Plain, where the hydrological cycle components and rain run-off process were replicated at the watershed scale [20].
- WEAP was implemented in the Djeffara-Medenine shallow aquifer in Tunisia to evaluate the groundwater spatial management and management of its amount, where 3 scenarios were mimicked to simulate irrigation water, population growth rate, as well as industry growth rate. The results signposted a future decrease in reservoir water amount due to intensive exploitation under limited recharge [21].
- A study was carried out to assess the Euphrates River in Ramadi City as well as the Al-Dhiban Canal for various purposes and to inspect the cations, anions, electrical conductivity, and TDS during 1992-1998. The results flagged out that Euphrates River water is suitable for drinking, irrigation, as well as for industrial purposes, in reference to Iraqi specifications [22].
- Under drought conditions in 2020-2022, various samples were taken and results indicate elevated concentrations of nitrate and silica in some streams and springs on Oahu, primarily reflecting the impact of historical use of sloping land for sugarcane cultivation rather than wastewater inputs [23].
- A study was conducted on samples from the Al-Warrar area of Ramadi City at different groundwater levels, where the results specified proportions of sulfate variations in water as well as soil physical as well as soil chemical properties [24].
- A study was carried out in the Al-Warrar area of Ramadi to designate a water quality index for domestic as well as agricultural use, where the laboratory analysis flagged out that there are significant differences between wells and the water quality of the Al-Warrar Canal. This is evident in the measured parameters, in terms of the World Health Organization. This was attributed to human activities (i.e., urban expansion, agricultural flooding, as well as discharge of untreated sewage) [25].

3. CASE STUDY

The considered case study of Al-Anbar Province is located in the western part of Iraq. The Euphrates River constitutes a vital water source in this area. Anbar is bordered by Nineveh Province at the north. It is bordered by KSA at the south. It is bordered by Babylon, Karbala, and Najaf to the east. It is bordered by Jordan and Syria at the west. The diversity of water resources in the Anbar area plays a significant role in delineating proper and sustainable water resource management. This section focuses on the site visits that were carried out to the study area. The section expounds the processes of site visits and data assembly. Moreover, the section provides data processing and a site description, as follows:

3.1 Site visits and data assembly

To increase the reliability of the proposed methodology and ensure that the specified requirements are sufficient and correct, several site visits were carried out to Al-Anbar Province (Figure 1). Where observations were documented, photos and videos were captured, measurements were undertaken, and a semi-structured interview was carried out with the local residents of the area to survey their perspectives about the study area.

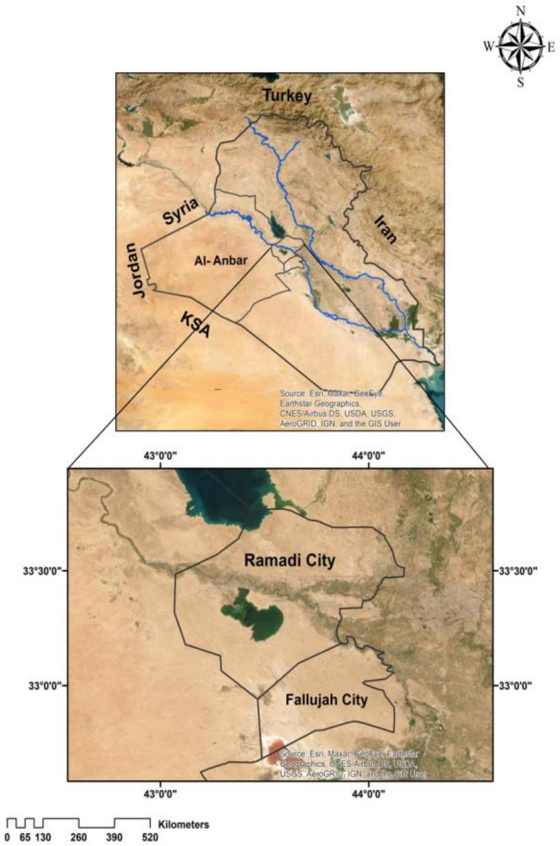

Figure 1. Study area location (ESRI imagery map)

3.2 Assembled data analysis and site description

The assembled data were analyzed, and the semi-structured interview responses were analyzed. Accordingly, a complete data picture about the study area was perceived, from which apparent was the following:

- Anbar area is 137,808 km^2, which forms 32% of Iraq [26].
- Anbar area lies within the latitudes (34°24'54") and (34°11'6") north.
- Anbar area lies between longitudes (40°28'12") and (41°25'48") east.
- Ramadi lies within the latitudes (33°48 - 33°07) to the north and longitudes (43°36 - 43°27) to the east.
- Fallujah lies within latitudes (33°21 - 33°47) to the north and longitudes (43°49 - 43°44) to the east [27].
- Euphrates runs through Fallujah administrative units. It is the main water resource for agricultural areas.
- Euphrates is the main artery of Anbar, which extends from its source in Turkey to its estuary in Iraq with a length of 2,940 km.
- Euphrates enters Al-Qaim District and runs through its administrative unit (i.e., Syria, as well as Turkey and Iraq).
- Euphrates runs 450 km in Anbar Province, where its length inside Iraq is 1160 km [28].
- Euphrates originates from the southern Turkey Mountains and extends over 1782 km before reaching the Iraqi-Syrian border.
- Euphrates extends 1178 and 604 km in Turkey and Syria, respectively [29].

4. WATER RESOURCES MANAGEMENT AND NUMERICAL INVESTIGATION

Concentrating on the water resources management, it encompasses several stages (i.e., estimating the needed amount of water for the domestic and agricultural sectors, as well as the yearly water coming from the Euphrates River, as well as the treated wastewater and groundwater).

Focusing on the numerical investigations, 3 scenarios were replicated (i.e., the 1st scenario implements surface water and was referred to as the “reference scenario," the 2nd scenario integrates treated water for irrigation, and the 3rd scenario integrates groundwater). This was achieved to simulate a 30-year period, 2010-2040.

5. NUMERICAL MODELING

This section elaborates on the available numerical models and the selected model while expounding its theoretical background, its calibration, and validation processes. Moreover, the section particularizes the numerical simulation process as follows:

5.1 Available numerical models

This section provides a summary of the available models that are analogous to WEAP. The section focuses on their identities and applications within the field of water resource management, as follows:

- Soil and Water Assessment Tool “SWAT”: It is a hydrological model that simulates the impact of management on water quality and quantity in large basins. It is distinguished by its integration to land use, soil, and weather data. It is capable of replicating agricultural practices, such as erosion, as well as sediment transport. It is applied within the fields of watershed management, pollution control, and land use planning.
- MODFLOW: It is software for groundwater modeling that was developed by U.S. Geological Survey. It simulates groundwater flow. It is distinguished by its ability to model the aquifer identities, replicating well interactions, and mimicking surface water/groundwater interaction. Its design allows many enhancements. It is applicable to groundwater assessment, contamination investigations, and aquifer management.
- Hydrologic Engineering Center's River Analysis System “HEC-RAS”: It is a model that simulates river hydraulics and analyzes floodplain hydraulics. It is distinguished by its performance within the domain of flow analysis, as 1-D and 2-D. It models

sediment transport and water quality, and applied in floodplain management, flood-risk-assessment, and hydraulic design.

- MIKE BASIN: It is a tool for water resources management, where it integrates surface water and demand management. It is characterized by its user-friendly interface during scenario analysis so as decision support. It supports scheduling of water resources. It is applicable within the domain of water allocation planning, so as drought management, as well as river basin management.
- Other models are available. Among them, for example are:
  - ✓ Aqueduct
  - ✓ CROPWAT
  - ✓ Spatially Explicit Water Assessment Tool "SPAWN"
  - ✓ WEAP

5.2 Historical and theoretical backgrounds of WEAP

WEAP was selected to be implemented, as it is worldwide accepted and was applied to many problems and proved its capability to resolve them. Moreover, it has a friendly interface and acquires limited data sets to initiate its calculation. Accordingly, it does not acquire further assumptions for unavailable data, which is the case in Iraq (Figure 2). The WEAP model is selected in this study as a comprehensive tool for planning and policy analysis. The most important advantage of this tool is its applicability to all individual watersheds, complex transboundary river basin systems, or agricultural and municipal systems. The model has a great ability to simulate a wide range of engineering and natural components of systems, including water demand analyses, water conservation, hydropower generation, water quality and pollution tracking, water allocation priorities, vulnerability assessments, stormwater runoff, baseflow, groundwater reuse from rainfall, ecosystem requirements, and reservoir operations. Consequently, it was selected to predict the annual water supply in the Euphrates.

Historically, WEAP was established in 1988, where it is being boosted by the U.S. Center of Stockholm in Somerville, Massachusetts.

Theoretically, WEAP augments groundwater flow module "USGS MODFLOW" and surface water quality module "US EPA QUAL2K". It is based on a hypothetical time-step water balance. It considers both demand and withdrawal [30].

WEAP is based on an efficient algorithm that solves water distribution problems while taking site demand into consideration and integrating the hydrological units (i.e., rain runoff and groundwater) [31]. It is capable of replicating climate change. It is employed by researchers and planners worldwide. It replicates water demand, such as runoff, as well as infiltration and crop irrigation requirements. This is attained by altering the policy, as well as climate and technology.

5.3 WEAP internal computation

This section expounds WEAP internal computation.

- Demand Supply "DS" is signified as the sum of inflows.
- Supply source "Src" is defined as the outflow of the transmission link that connects them.
- The net of any leakage is designated along the transmission link [21], Eq. (1), as follows:

$$\text{Demand / Site Inflow DS} = \text{Trans Link Outflow (Src, DS)} \quad (1)$$

- Demand, at some demand sites, "*DS*" is computed (sum of corresponding demands of all bottom-level Branches "Br" of that site [20], Eq. (2), as follows:

$$DS=\sum_{Br} \textit{Annual Demand} \; (\textit{Total Activity Level} \; \text{"}Br\text{"} \times \textit{Water Use Rate} Br) \quad (2)$$

- Unmet demand is assigned if any site demand is not met (i.e., demand sites are not fully covered).
- The total groundwater storage is estimated in Eq. (3) by assuming that the groundwater table is in equilibrium with river, where the equilibrium storage for any wedge site "GS_e", as follows:

$$GS_e = (h_d)(l_w)(A_d)(S_y) \quad (3)$$

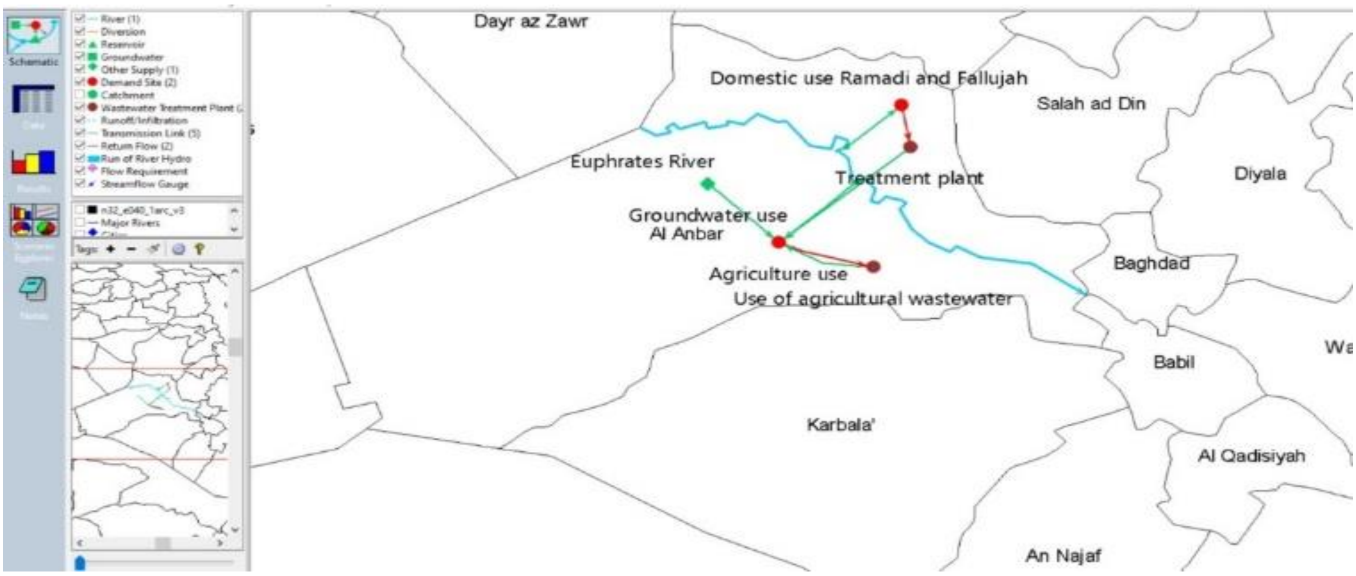

Figure 2. WEAP interface

5.4 Modeling Anbar numerically

Before implementing the model, it was calibrated by tuning it parameters to force it produce data similar to the observed data. Moreover, it was verified against real data. Confident with the calibration and verification results, it was implemented to simulate Anbar Providence. This is presented as follows:

5.4.1 Calibrating and verifying WEAP

WEAP was calibrated against actual data sets. It was then verified against another actual data set. These data were assembled during the site visits.

5.4.2 Applying WEAP to simulate Anbar

Confident with the calibration and validation results, WEAP was utilized to simulate Anbar, where the water demand was predicted, in the domestic and agricultural sectors in Ramadi and Fallujah, over 30 years (i.e., 2010-2040). WEAP simulated 3 scenarios. The 1st scenario was the reference scenario of the existing condition that utilized surface water only, while the 2nd scenario implied the additional use of treated wastewater. However, the 3rd scenario implied the additional utilization of groundwater.

5.4.3 Preparing WEAP input data

Regarding WEAP input requirements, Euphrates discharge is measured from two control stations, and the portion of each city was acquired from the Directorate water resources planning department and they encompassed the following:

- The calculation considered 2010 to be the starting simulation period for Euphrates in Anbar for Ramadi and Fallujah. Where the regional population survey water needs for the region were utilized
- The population growth rate was estimated based on the announced 2008 population and the growth for years 2011-2040 was considered.
- The actual consumption was assumed to be 15% of consumption losses.
- The lost water by evaporation and treatment was not considered as it was unrecorded.
- The domestic use was prioritized to meet the demand.
- Based on the National Commite on Population Policy in Anbar Providence, the cities of Ramadi and Fallujah were assigned to constitute 36.37 and 35.69% of the province total population, respectively.
- The agricultural sector water needs were assigned according the annual plans of the agricultural areas decided by Anbar Agriculture Directorate.
- The 2nd scenario considered the water regained by the sewage network, where such data were assembled from treatment plants in the study area [32].
- The 3rd scenario considered the data of wells within the region, where they were classified, in terms of the discharge and percentage of appropriate as well as inappropriate salts, as shown in Figures 3 and 4. However, the appropriate well water for drinking so as irrigation were accounted for [33].
- The computation utilized the available Euphrates discharge during 2010-2023.

Figure 4 elaborates the implementation methodology of WEAP. Moreover, the figure clarifies scenario development and the managing strategies for assessing and planning future water.

Table 1. Euphrates annual flow and share of Ramadi and Fallujah (during 2010-2040)

Inflows to Area (Cubic Meter)			
Year	**Euphrates Flow**	**Year**	**Euphrates Future Flow**
2010	1,669,338,800	2024	1,647,753,000
2011	1,654,688,000	2025	1,630,724,000
2012	2,308,744,000	2026	1,613,689,000
2013	1,719,019,000	2027	1,596,030,000
2014	1,758,439,000	2028	1,579,002,000
2015	847,372,100	2029	1,561,339,000
2016	1,716,500,000	2030	1,543,998,000
2017	1,491,013,000	2031	1,526,652,000
2018	1,083,261,300	2032	1,509,310,000
2019	1,625,674,000	2033	1,491,965,000
2020	1,682,757,000	2034	1,474,612,000
2021	1,689,065,000	2035	1,457,271,000
2022	1,679,286,000	2036	1,439,925,000
2023	1,664,460,000	2037	1,422,266,000
		2038	1,405,238,000
		2039	1,387,579,000
		2040	1,370,551,000

Furthermore, Table 1 elaborates the Ramadi and Fallujah share based on the annual flow of the Euphrates River in Anbar during 2010 to 2024. These data were extracted from Al-Qaim Station.

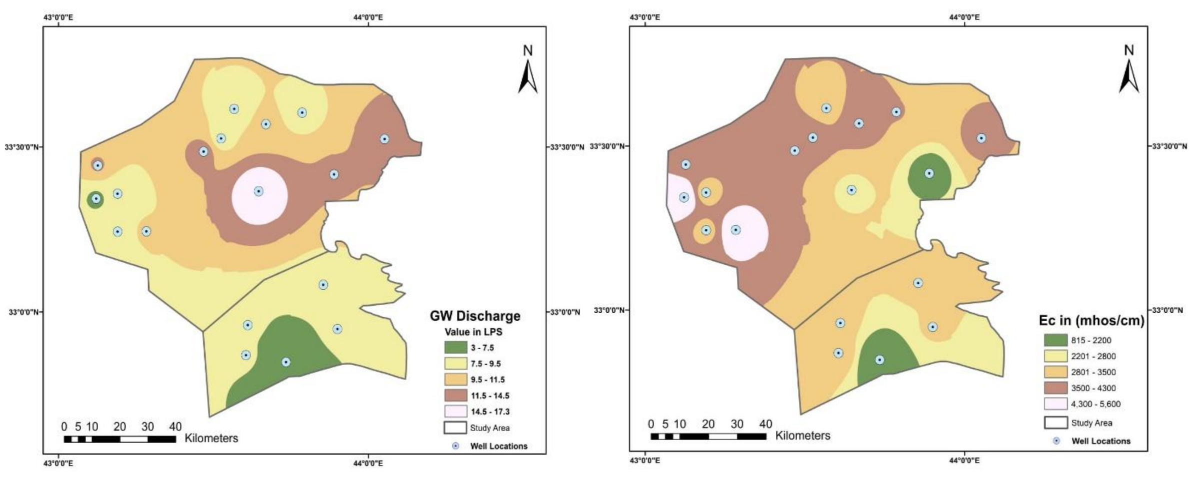

Figure 3. Well distribution based on water amount, salinity and utilization capability

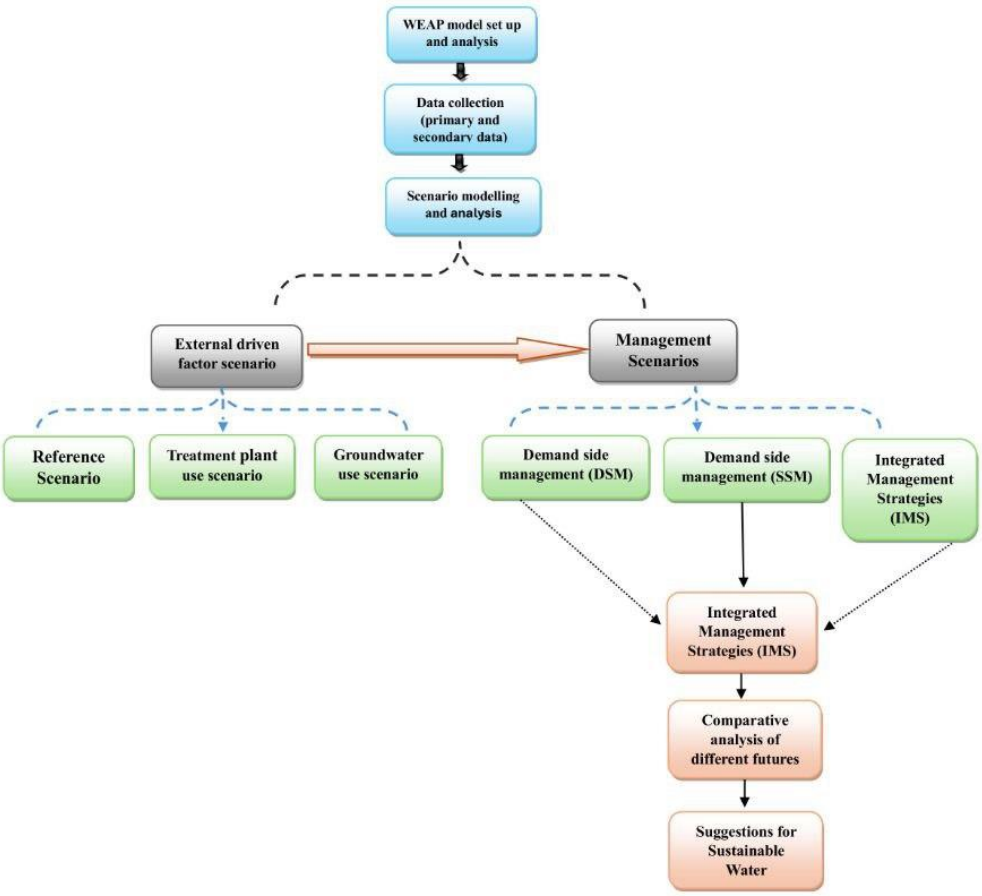

Figure 4. WEAP assessment and planning

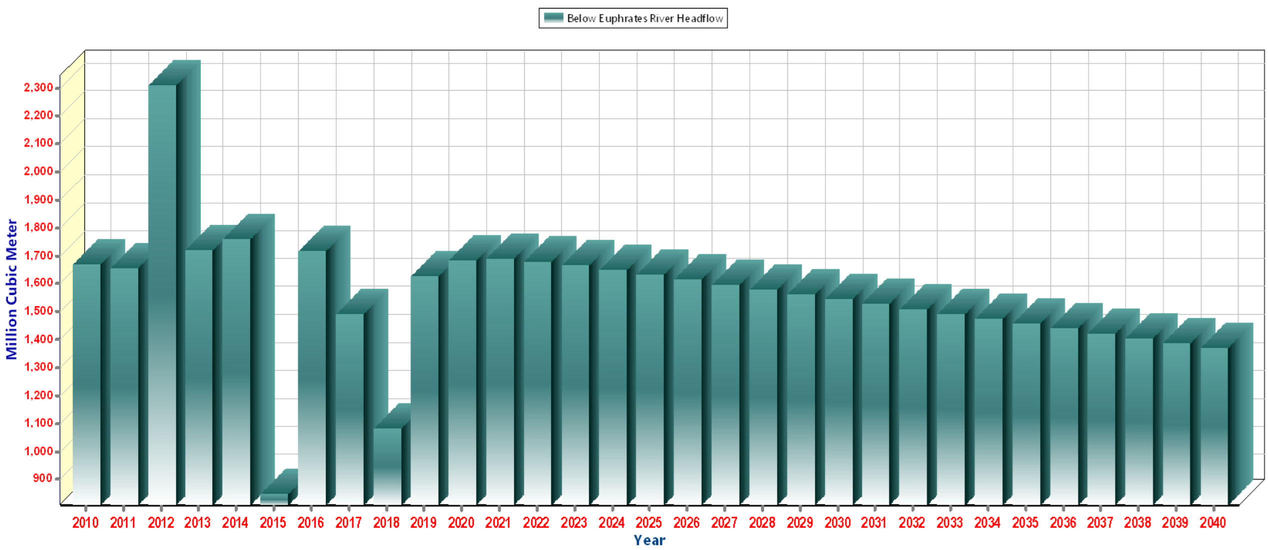

Figure 5. Euphrates annual flow share of Ramadi and Fallujah cities (During 2010-2040)

Moreover, during 2024 to 2040, the forecasts for Ramadi and Fallujah share were extracted from Euphrates annual flows, where Figure 5 presents the utilized forecast of Euphrates River water flows till 2040.

6. RESULTS ANALYSIS AND DISCUSSION

Results were obtained, analyzed, and represented on graphs in Figures 5 to 10, as follows:

Figure 5 shows the flows of the Euphrates River from 2010 to 2040. The results indicate a continuous decrease in the river's discharge in the future due to climate change, drought, and incorrect water policy between countries. Figure 6 presents the future water demand for the 1st reference scenario in Fallujah and Ramadi within the domestic sector. The figure also indicates the continuous increase in the amount of water required for the two regions due to the increase in population growth, urban expansion, and climate change, and thus it prompts us to think about finding solutions and alternatives to cover the demand in the future. Figure 7 presents the future water demand for the 1st reference scenario in Fallujah and Ramadi within domestic and agricultural sectors. Therefore, we find a large difference in the amount of water required between the two sectors, which indicates a great risk of water scarcity, as the agricultural sector consumes the largest amount of water due to the increase in agricultural areas and the large agricultural consumption of agricultural crops and their dependence on surface water only in this region. Figure 8 highlights the future unmet demand for the 1st reference scenario in Fallujah and Ramadi within domestic and agricultural sectors. Where the WEAP model shows us future signals in the amount of unmet demand for water for the domestic and agricultural sectors, and thus it gives us numbers and predictive quantities of future water needs, and this large difference indicates the trend towards using alternatives to surface water to reduce the deficit and the outlook for water in the future. Figure 9 illustrates the flow and actual water consumption, along with the treated water usage in the urban domestic sector of Ramadi and Fallujah, where sewage networks are utilised for treatment under the 3rd scenario. This scenario contributes to support water management and reduce the unmet demand for water in the reference scenario, and thus there will be future planning to rationalize water and benefit from treating this water in the and agricultural sectors. Figure 10 shows the water demand of the 3rd scenario as an alternative to reduce unmet This scenario is one of the most important solutions for using alternative water to cover the unmet demand, as groundwater is one of the most important alternatives to surface water, especially in the agricultural sector, as it consumes the most water. Therefore, the results indicate the necessity of using this scenario at present and in the future. The figures highlighted the importance of putting forward a future plan to cover water shortage under water scarcity risks.

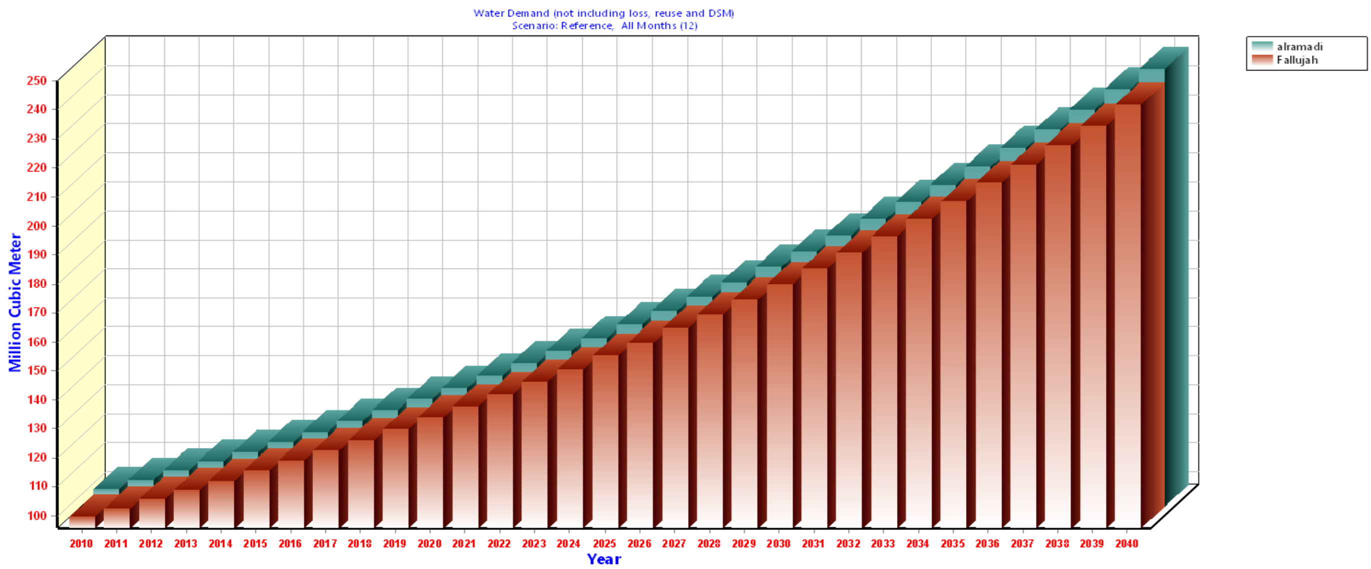

Figure 6. 1st scenario results (reference case) of domestic sector demand for Ramadi and Fallujah (During 2010-2040)

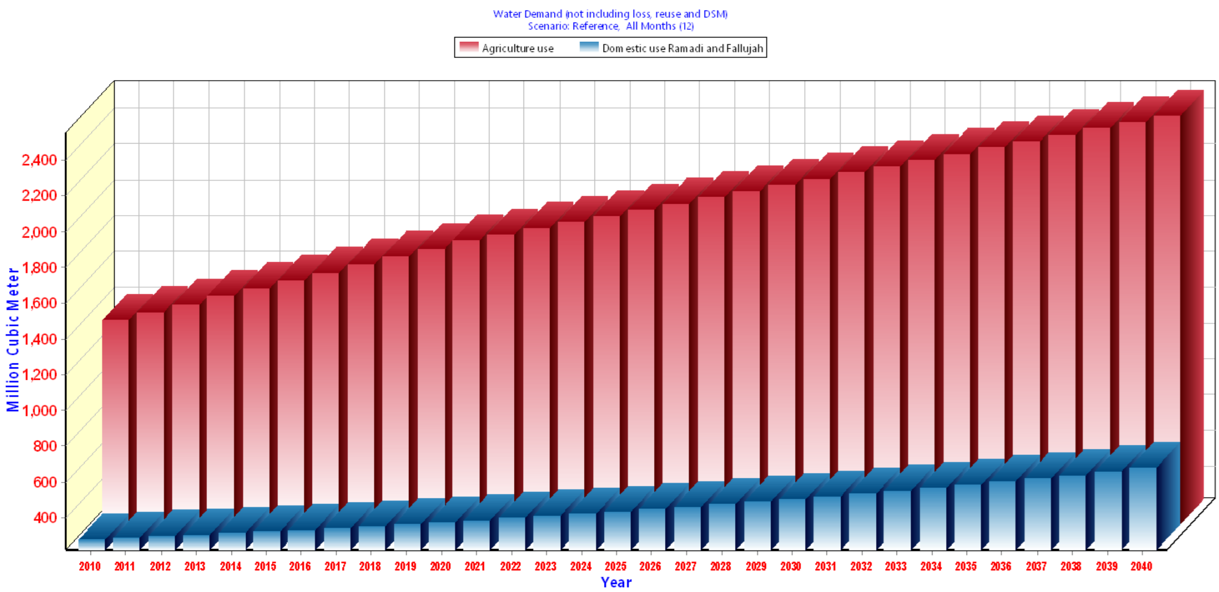

Figure 7. 1st scenario results (reference case) of domestic and agricultural sectors demand for Ramadi and Fallujah (During 2010-2040)

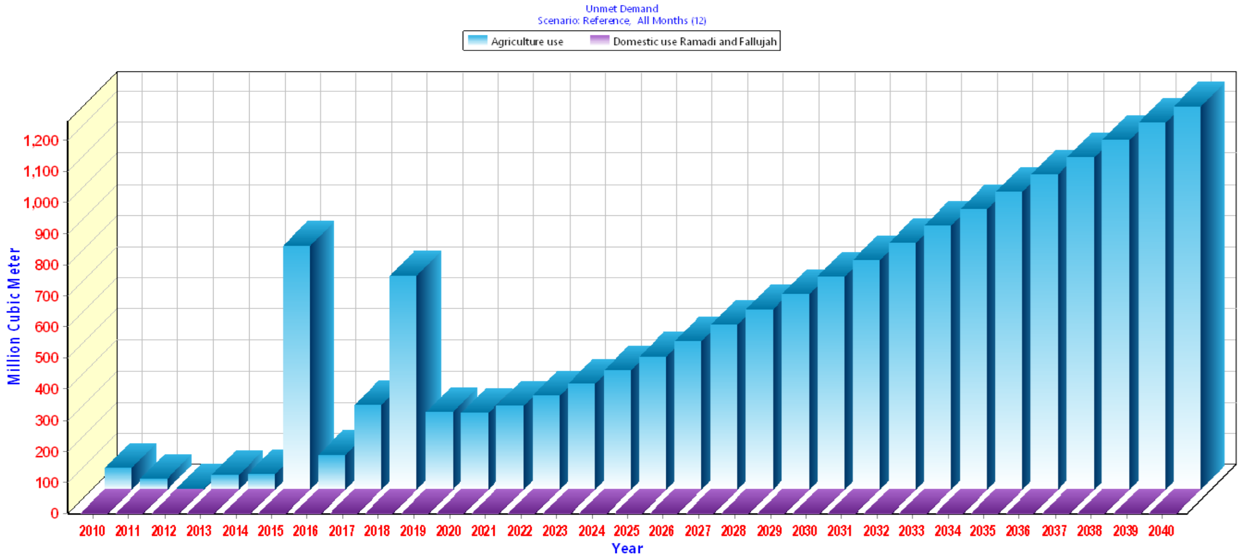

Figure 8. 1st scenario results (reference case) of unmet demand for domestic and agricultural sectors for Ramadi and Fallujah (During 2010-2040)

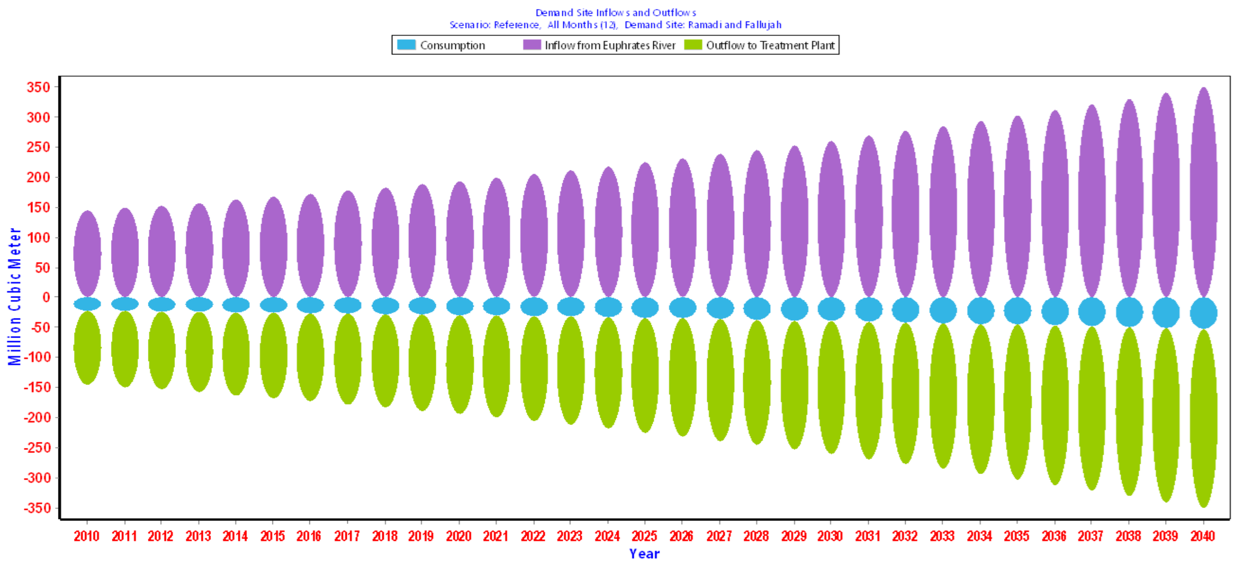

Figure 9. 2nd scenario results (treated water) of Inflow vs. consumption for Ramadi and Fallujah domestic sectors (During 2010-2040)

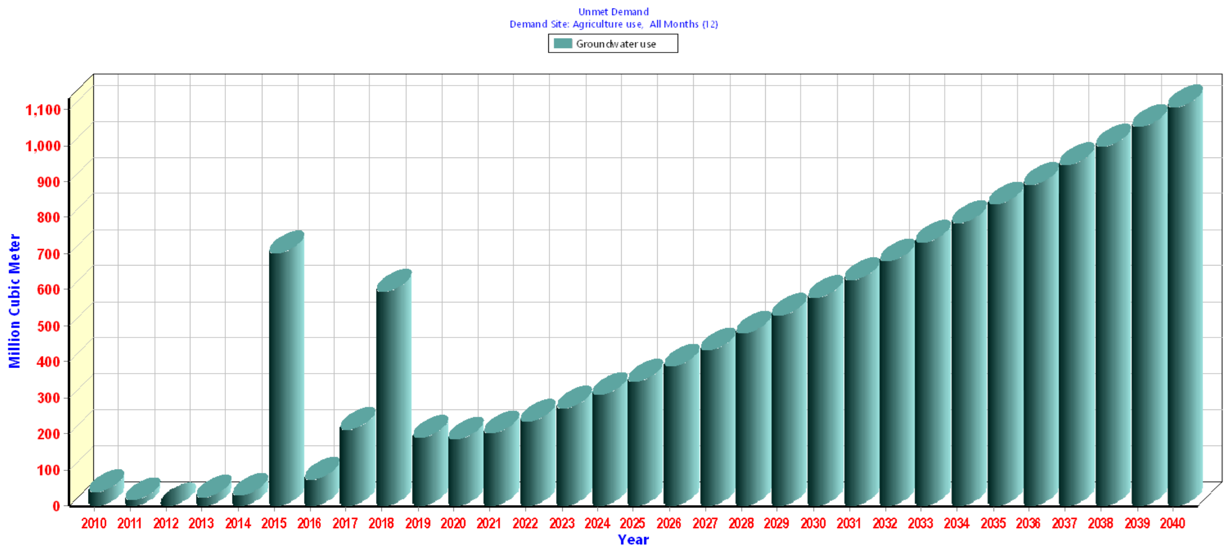

Figure 10. 3rd scenario results (groundwater use) of unmet demand for water for agricultural sector for Ramadi and Fallujah (During 2010-2040)

7. CONCLUSIONS

Based on the present investigation, apparent was the following:

- Euphrates discharge decreased due to climate change and the implementation of an unfavorable water strategy that does not cope with unmet demand for water in the domestic and agricultural sectors, under the existing conditions of population growth and agricultural area expansion.
- Focusing on the water demand, it was doubled in the 1st scenario over 30 years (i.e., it increased from 1560,052 to 2987,688 $\times 10^6$ m^3). This is attributed to the population growth, investment increment in agricultural areas and future extension to the lands in Anbar.
- Converging on unmet demand, it attained 16.939 $\times 10^6$ m^3 in 1st scenario.
- The 1st, 2nd and 3rd scenarios unmet the water demand in 2040 by 16.939, 6.131 and 14.355 × 106 m^3, respectively, where the 2nd and 3rd scenarios covered 36 and 84% of water shortage, in reference to the base case (i.e., 1st scenario), respectively.

8. RECOMMENDATIONS

Based on the deduced conclusions, the following recommendations were suggested:

- Implement treated water and groundwater to reduce water shortages to achieve promising integrated management within the domain of agricultural and local sectors, thus, it will be a supporter of surface water and a successful alternative in water resources management.
- Applying new solutions to enhance the utilization of surface water (i.e. reusing treated water and utilizing groundwater to achieve integrated management in all available water resources).
- Apply novel solutions to boost the utilization of surface water (i.e. reuse of treated water and utilizing groundwater).
- Reuse agricultural drainage water. There is a large amount of water that can be used and reused in agricultural irrigation to achieve sustainable water management.
- Employ saline water from wells and mix it with fresh water.
- Implement salt-resistant crops (i.e., trees resisting winds and dust and stabilize the soil).

Employ modern irrigation to achieve sustainability in the agricultural sector such, such as using of drip and sprinkler irrigation methods, as they are among the latest methods in rationalizing water consumption, especially in the water needs of plants, and avoiding irrigation methods.

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