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Article

Assessment of Water Characteristics in the Tigris and Euphrates Rivers and Identification of the Appropriate Treatment Method base on Population Densities

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Abstract: In Iraq, Tigris and Euphrates Rivers are the primary freshwater sources, which are becoming endangered due to population growth, urbanization, industrial effluents, agricultural run-off and climate change. These have greatly affected river physical, chemical and biological qualities, particularly in high population density areas. The purpose of this review is to evaluate water quality characteristics of Tigris and Euphrates Rivers and determine most proper treatment methods based on the population densities and pollution levels. However, recent studies have shown that salinity, nutrient, heavy metal, organic contaminant, and microbial contamination levels are increased in several areas of both rivers, particularly in the downstream urban areas. Water Quality Index and statistical analyses are also emphasised as important tools to assess river-water quality and pollution sources. Conventional treatment technologies can be used at low to moderate levels of contamination while advanced treatment technologies (such as reverse osmosis and membrane filtration) work best in highly populated areas with high levels of contamination. The research highlights the need of sustainable water management strategies and enhancing wastewater treatment facilities to safeguard Iraq's precious water resources.

Keywords: Assessment of Water, Tigris, Euphrates

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1. Introduction

Iraq's main freshwater resources are the Tigris and Euphrates Rivers, which serve as foundation for the country's industrial, agricultural, and residential water supplies. The physicochemical and ecological properties of these rivers have been profoundly impacted by rapid population increase, urbanization, industrial discharge, agricultural runoff, and climate change. In heavily populated regions like Baghdad, Basra, Mosul, and Al-Amarah, where untreated municipal wastewater is regularly dumped straight into river systems, the degradation of water quality has gotten worse [1].

The terrain is primarily desert, with dry, hot, cloudless summers and warm to chilly winters. Along the southern Iranian border are reedy marshes with huge, flooded regions. Turkey, Syria, and Iran share their water resources from the Tigris and Euphrates River systems, where they combine and create the Shatt al Arab to the south prior to discharging into the Arabian Gulf. Turkey contributes more than 90% of Euphrates yearly discharge and nearly 38% of the Tigris flow, allowing it to influence the downstream discharge of the rivers. Only 18.1% of the land is used for agriculture, consisting of 9.2% permanent pasture, 0.5% permanent crops, and 8.4% arable land[2]. Iraq depends on irrigation in the south and rain across the northern regions. Wheat, barley, rice, vegetables, dates, cotton, cattle, sheep, and poultry are mostly found mainly in the eastern and southern areas of Samarra. However, the lack of employment opportunities and the agricultural sector drive migration to urban areas, which make urban poverty worse [3].

Farming systems are a result of population increase and the need to produce more food from a finite supply of land and water that frequently prioritize short-term profits over long-term viability. Markets and desires for manufacturing efficiency are severely distorted by government subsidy programs. The most overstressed aquifer system in the world is the Arabian Aquifer System, which is shared by many Middle Eastern nations, along with the Euphrates and Tigris River systems. Upstream diversions have diminished these river systems, and more are anticipated in the next 20 years, potentially lowering Iraq's water supply by as much by up to 60% [4].

The volume of treated sewage waste in Iraq is estimated approximately 580 million m3. Farmers use the majority of untreated wastewater to irrigate nonfood crops including clover, cotton, and sunflowers as well as certain edible crops like lettuce, cabbage, peppers, tomatoes, and beans. WWTPs may exacerbate river pollution by releasing cleaned wastewater without adhering to national environmental rules. Unfortunately, Iraq's infrastructure is plagued by numerous issues, including excessive water use in antiquated irrigation systems, water loss through its water distribution networks, and backwater from irrigation and sewage contaminating freshwater sources. According to Al-Ansari, the distribution network's efficiency is extremely low (32%) and is getting worse with time. Drinking water quality frequently falls short of

Iraqi national water quality requirements or World Health Organization (WHO) standards, and high levels of contaminated sewage water leaks endangers networks of drinkable water. An estimated 0.5 MCM of untreated wastewater is released into waterways every day. Iraq's national water system has been severely damaged as a result of decades of conflict, sanctions, and a lack of environmental knowledge among the populace and government officials [5].

There are three primary sources of groundwater recharge: precipitation, surface water infiltration, and artificial irrigation in agriculture [6]. Recharge rates are between 100 and 300 mm/yr, and it mostly happens in Iraq's northern, rainier regions. Recharge of groundwater in at little than 20 mm/yr, the south is insignificant. The yearly recharge and sustainable groundwater supply are insufficient to restore current groundwater supplies, which Iraq's riparian neighbors upstream are expected to remove, severely harming it.

Near 2019, the Iraqi government constructed Iraq's first large desalination plant near Al-Hartha, approximately 20 kilometers north of Basra, which somewhat offsets this. In order to make use of excess heat and use temperature-controlled heat processes designed to prevent scale formation, thermal desalination—including technologies such as Multi-Effect Desalination (MED) and Multi-Stage Flash (MSF) techniques—is usually used in conjunction with thermal power plants [7]. The another widely used desalination technique is relies on membrane separation, commonly referred to as reverse osmosis (RO), currently regarded as one of the most widely applied des because of developments in membrane technology. 199,000 m^3 of brackish water may be desalinated by the reverse osmosis system. It is a component of a bigger government initiative to enhance the Basra governorate's water supply. There are presently plans underway to build a second major desalination plant on the Gulf coastline in Al-Fao. This might make use of an RO plant or MSF, or a mix of these approaches until more sophisticated membrane technologies become more advanced.

In most areas, RO offers a number of benefits. Usually, it consumes half as much energy as thermal processes. However, membranes are susceptible to microbial fouling, and extensive pretreatment is needed for water with high silt content, as the Shatt al Arab. Iraq's water resources are managed in large part via rainwater collection projects, which typically take the shape of dams along wadis. They enable the retention of rainfall following intense downpours, which can then be used to replenish groundwater supplies. However, the accumulation of sediment in the reservoirs of several of these dams has diminished their storage capacity.

Due to inadequate WWTP infrastructure capacity throughout nation, especially in rural regions, and a lack awareness regarding the effective reuse of wastewater, there is currently very little treated wastewater reuse in Iraq. It is advised to use treated wastewater for municipal purposes like street cleaning and park watering, as well as agricultural purposes like fodder irrigation. Only a small percentage of drainage water is collected and utilized; the majority is returned to rivers due to Iraq's low overall irrigation efficiency. In order to properly reuse irrigation water, which is essential to supplying the nation's future water needs, the Ministry of Water Resources intends to update its drainage water collection system.

The scale of infrastructure pressure reported for Iraq is summarized in Figure 1. The indicators show that water-quality deterioration is linked not only to pollutant generation, but also to limited wastewater-treatment coverage and high losses in water-distribution systems.

2. Materials and Methods



Figure 1. Selected quantified pressures on Iraq's water and wastewater systems. Source: Al-Ansari et al. (2014, 2015).

River water quality plays a significant function in supporting human consumption as well as natural ecosystems. Water from rivers can be used for drinking, sectors of manufacturing and agriculture. However, chemical, physical, and biological processes can have a direct impact on surface water quality, which essentially clarified a crucial environmental issue [8]. To maintain the acceptable quality of surface water, it is especially important to control pollution concentrations along rivers [9]. Physical water parameters include things like temperature, turbidity, electrical conductivity (EC), total suspended solids (TSS), and total dissolved solids (TDS). Research along the Euphrates River revealed rising salinity and turbidity downstream as a result of sewage disposal and agricultural drainage. In southern Iraq, salinity levels frequently above acceptable drinking water limits, particularly in close proximity to densely populated areas [10].

Since the beginning of the twenty-first century, hydrological science has made significant strides in addressing the related worries about water scarcity [11]. Interestingly, the study showed that ion concentrations varied both seasonally and geographically. As a result, throughout time, a number of anthropogenic and natural factors, mostly unregulated releases of hazardous and

industrial wastewater, had a passive impact on surface water quality [12].

In a similar vein, the Tigris River exhibits regional differences in water quality. Compared to southern stations like Al-Amarah, where pollution accumulation significantly rises, northern sites around Mosul often have superior water quality. Inadequate wastewater treatment infrastructure, industrial activity, and population density are all linked to the degradation [13]. Monitoring river water quality is essential for providing field data for effective water management. The functioning and disposal of the river's effluent depend on these statistics. One of the easiest methods to assess the condition of the municipal water supply is to use water quality indices. It is used for both groundwater and surface water.

The north-south contrast is quantified in Figure 2. Hadi and Al-Juhaishi [14] reported CCME-WQI values of 83-94 in Mosul and 52-59 in Al-Amarah, indicating a shift from good quality in the north to marginal quality farther downstream.

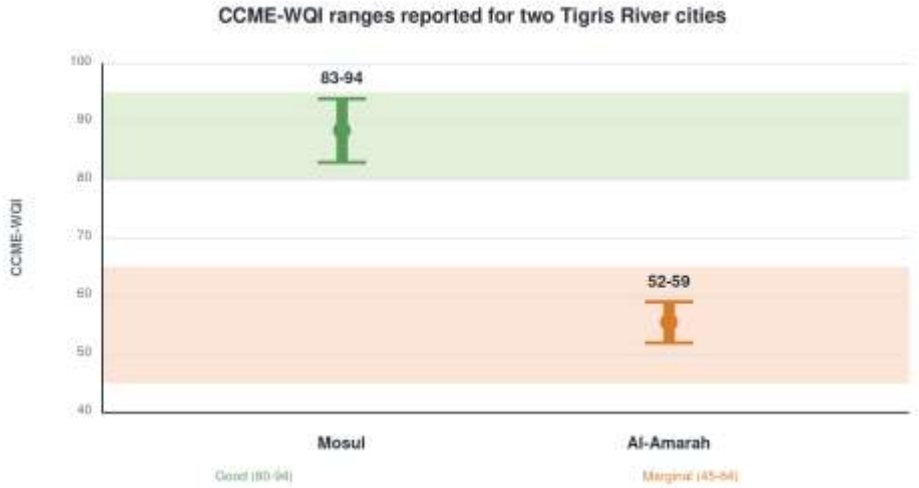


Figure 2. Reported CCME-WQI ranges for the Tigris River in Mosul and Al-Amarah. Source: Hadi and Al-Juhaishi (2023).

Water management requires an awareness of the variations in physicochemical parameter values of water quality as well as the effects and fluctuations of biogeochemical processes [15]. Chemical factors, such as pH, dissolved oxygen (DO), BOD, chemical oxygen demand (COD), nitrates, phosphates, sulfates, chlorides, and heavy metals, are crucial markers of river pollution. Because river systems carry pollutants and other elements from all over the world, majority of a river's water is contaminated by high pollution loads river flow [16]. Water pollution is largely caused by urbanization [17]. The direct disposal of wastewater, which contains detergents, acids, alkalis, dyes, heavy metals, and other toxins, affects the quality of the water [18]. The public's awareness of water pollution has grown in recent years.

Additionally, research on the Euphrates River showed that agricultural runoff has a major role in the enrichment of phosphate and nitrate, which leads to eutrophication and algal blooms in a number of areas. The cumulative effects of population growth and human activity are reflected in the ongoing rise of pollutants downstream. In other words, Complex hydrogeochemical processes, like the dissolving of salts from nearby evaporate deposits; can affect the quality of river water. Additionally, untreated sewage and irrigation return flows can adversely affect the river's inherent capacity for self-purification, resulting in altered patterns and pollution immigration that have notable ecological affects downstream [19].

Numerous studies have documented high levels of lead, cadmium, chromium, and copper in various parts of Iraqi waters, including (Al-Bahathy and Nashaat [20], Majeed [21] Aljanabi [22], Nashaat and Al-Bahathy [23], Majeed [24]. Organic pollution from densely populated cities was closely associated with elevated BOD and COD levels. New methods for putting long-term water

management into practice were therefore taken into consideration. As a result, it is crucial to regularly assess water resources to ascertain the quality of water for different purposes [25].

Al-Sarra j [26] presented a thorough analysis to examine fish tissues, sediment, and water quality in addition to defining heavy metals such as chromium, lead, arsenic, mercury, and cadmium. In addition to insufficient seasonal or regional examination of metal distributions, this review examined the scant epidemiological studies on the consequences of pollution on human health. Environmental geochemistry of Euphrates River from AlQaim to Basrah was examined by Muslim [27], indicating changes in sediment quality, especially ion composition.

One of Iraq's most pressing public health issues is biological pollution, also Surface water quality plays a major part in aquatic biota biological processes, is highly susceptible to human activity, and is essential for both environmental sustainability and economic growth [28]. Numerous areas of both rivers have been shown to contain high amounts of harmful bacteria, such as fecal and total coliforms. Untreated sewage discharge from cities with inadequate wastewater treatment infrastructure is the primary cause of the contamination. In many Iraqi provinces, poor water quality is still linked to waterborne illnesses like cholera, typhoid, and gastroenteritis.

Waterborne infections are prevalent due to contaminated drinking water supplies. The levels of bacterial contamination in water supplies, which vary from governorates with an average of 16% and a range of 2.5% to 30%, exceed both Iraq's National Drinking Water Standards and the World Health Organization's Guidelines for Drinking Water, according to Ministry of Environment reports from 2009. Along with suspended and dissolved contaminants, Iraqi rivers are heavily contaminated by solid trash, including industrial and domestic waste, as well as debris from structures that have been damaged in places affected by previous hostilities. Hepatitis A, typhoid fever, and bacterial diarrhea are the main foodborne or waterborne illnesses in Iraq, along with schistosomiasis and leptospirosis [29].

For nearly ten years, the water supply of Basra, the second-largest city, has been poisoned, putting the health of its citizens at risk. In the meantime, poor water quality has also plagued a number of other regions in the nation. The 1.2 million people who live in Basra have endured this contamination. The Tigris and Euphrates rivers converge to form the Shatt Al-Arab River, provides the city with its water, but it is now overflowing with sewage, industrial trash, and a high proportion of salt. More than 277,000 students in Basra's schools are at risk of contracting a waterborne illness that manifests as rash, vomiting, and diarrhea due to the breakdown of proper sanitary facilities [30].

Numerous factors have contributed to this scenario, including loose sewage and industrial waste regulations, and a general lack of knowledge about proper waste disposal techniques. Reduced water flows during times of little rainfall contribute to the Persian Gulf's saltwater backflow into the Shatt al-Arab, which has salinities 50 times higher than those considered safe for drinking. Aquatic life, agricultural yields, and people have all been impacted. The oil-rich province of Basra suffers from water scarcity as well as frequent power outages, a stagnant economy, poor health care, widespread corruption, unemployment, and a drought-ravaged agriculture sector. At least 118,000 hospital admissions from people who claimed to have been poisoned by contaminated water contributed to the rise in violent protests in 2018. Foodborne and waterborne illnesses are largely spread by viruses, and WW is a significant source of these illnesses. Infected people sweat large amounts of human noroviruses and astroviruses.

They remain in wastewater for a very long time, endangering human health worldwide. By employing PCR sequencing and phylogenetic analysis to genotype WW samples from sewage water plants and draining canals in the Iraqi region, Hamad [31] discovered high detection rates of these pathogens. The paper claims that using molecular methods to record the sewage virome provides information for molecular epidemiology and may be useful in developing strategies to halt the spread of viruses. Al Nasrawi [32] describe an outbreak of the hepatitis E virus (HEV) in Al-Sadr city, Baghdad. 38.1% of 268 people with jaundice who visited 19 basic healthcare facilities in Al-Sadr city over a six-month period in 2005 had blood samples taken from people who had HEV IgM antibodies. Unacceptable residual chlorine concentrations and/or bacteriologically hazardous water samples

were significantly linked to HEV infection. High incidences of HEV infection, low chlorine levels, and tainted water were reported in June 2005. Severe disruption of water and sanitation services was shown to be the most likely source of these illnesses.

Over 3300 cholera cases tested positive for Vibrio cholerae in 2007, and over 30,000 persons experienced acute watery diarrhea [33]. The bulk of laboratory-confirmed cases of acute watery diarrhea occurred in Kirkuk and Sulaymaniah in the north, despite an increasing number of cases being recorded in the south. These incidents were linked to poor sanitation and water systems, which greatly raise the risk of cholera infection. Usually, this is a waterborne sickness. The reason of the ongoing outbreak was the increasingly common practice of irrigating vegetables with sewage water as a result of water shortages in the Tigris and Euphrates rivers. Sadly, some individuals are unwilling to drink water treated with Aqua tabs (which release hypochlorous acid) because they believe the natural flavor has been lost due to the COVID-19 epidemic and the already unstable state of the overworked system for national health.

Al-Kubaisy [34] estimated that 22% of people in Al Sadr city had parasite diarrhea; high household size was one of the primary predictors of diarrhea, along with residential location, water source, and low socioeconomic position. With an infection incidence of 45.5%, *Giardia lamblia* was the most common parasite, followed by *Ascaris lumbricoides* (2.2%), *Entamoeba histolytica* (23.4%), and *Enterobius vermicularis* (12.7%). This study demonstrated that the main factors that made children more susceptible to parasite diarrhea were low socioeconomic status, unfavorable environmental conditions, and inadequate sanitation.

One of the main variables affecting river pollution levels is thought to be population density. High population densities generate more solid waste, industrial effluents, and home wastewater, all of which eventually find their way into adjacent water bodies [35]. Baghdad, the most populated city along the Tigris River, has severe water quality degradation as a result of overworked sewage treatment systems and direct discharge of untreated wastewater. Water quality indices significantly decline downstream of urban areas, according to research. Similar to this, southern Iraqi cities near the Euphrates River exhibit higher salinity, nutrient concentrations, and microbial pollution as a result of population growth and intensified agriculture. The relationship between population density and pollution accumulation has been repeatedly demonstrated by recent environmental research. However, it is difficult to generalize overall pattern of water quality across geography and time [36].

In order to control these sources of pollution, detect any effects on aquatic systems, and assist health authorities in lowering pollution and ensuring the safe use of surface water for drinking plants, water quality monitoring programs must be established [37]. Additionally, Iraq's inadequate management of its water resources has resulted in a reduction in the quality of the river water. Water quality monitoring is unregulated in Iraq due to the country's unstable environment and lack of financing. Therefore, river water quality simulation is crucial in emerging nations like Iraq [38].

Water Quality Index (WQI) is a numerical index that takes several physicochemical and biological factors into consideration and is commonly used for a general evaluation of the health of rivers.A number of studies in Iraq were conducted to assess the conditions of the rivers using the Canadian Council of Ministers of Environment (CCME) Water Quality Index (WQI). Water quality was found to be "good" at the northern part of the study area, "marginal" in other urban centers and "poor" in south [39].

The use of aggregation techniques to simplify the description of the data and include in a single number or index, the overall state of water quality that can be assessed by WQI [40]. The British Colombia WQI Model (BCWQI) was updated to become the CCME WQI in 2001, to simplify and focus on water quality data. Easily applied and a model that can include a range of water quality data, it is often used. Numerous studies on assessing various water quality index models in various areas along Euphrates and Tigris rivers have been published in literature.

The BWQI results of Alharbawee [41] are plotted in Figure 3 in more detail along the longitudinal axis. The index fell at Balad from 70.00 to 57.08 at Jisr Diyala, the lowest drop at the two stations in the south of Baghdad. The values of BWQI and CCME-WQI should not be combined

directly as they are based on different formulations.

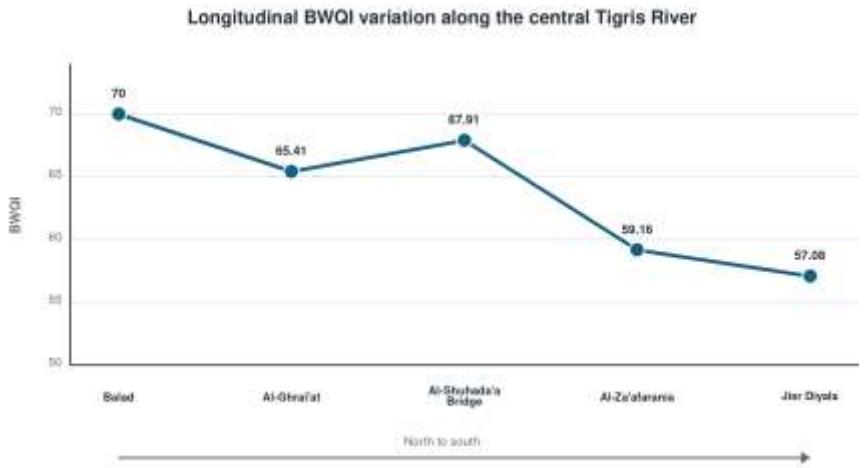


Figure 3. BWQI values at five stations along the central Tigris River (October 2021-September 2022). Source: Alharbawee et al. (2023).

Nevertheless, only a small number of studies evaluated the CCME WQI model. For example, twelve water quality criteria were chosen and the CCME WQI was computed for the Tigris River in Baghdad in 2010. The findings showed that the water at stations 1 and 2, which were situated north of Baghdad, was less contaminated than the water at station 3, which was located in the south. According to Al-Janabi [42], the CCME WQI ranking ranged from poor in station 3 to marginal in stations 1 and 2. Ten water quality measures were employed at various places (stations) along Al-Hussainiya River in Karbala City for 2016 CCME WQI evaluation. Every station had a low CCME WQI ranking.

Twelve water quality metrics were used to calculate the CCME WQI along Tigris River in the Wassit Governorate over a 12-month period, from October 2015 to September 2016. The calculated CCME WQI values, which range from 65 to 79, were in class fair (Mahmood, 2018). Using CCME WQI, impact of Al-Rasheed power plant (RPP) in Al-Zafaraniya City, Baghdad, was examined; eleven parameters were examined in six stations. Study's findings showed that the river water quality is significantly impacted by the RPP effluents' disposal. The water's temperature, electrical conductivity, turbidity, phosphate, and hardness have all significantly increased. For every season but winter, the Tigris River's water quality was rated as fair to marginal. In village of Shouira in Talafar district, the suitability of groundwater for drinking and indoor and outdoor household uses was assessed using CCME WQI; thirteen criteria were examined for fifty groundwater samples. The findings showed that the quality of groundwater was unfit for human consumption. The low oxygen values were the primary cause of CCME WQI's low value, which varied from 17.9 to 32.7 and fell into the bad category [43].

Seasonal and intended-use differences are also important. Figure 4 shows that the drinking-water index was the lowest component in every season near Al-Rasheed power plant, whereas the aquatic-life index was higher. The values nevertheless remained within poor-to-fair classes, demonstrating why a single annual average can conceal operationally relevant variation.

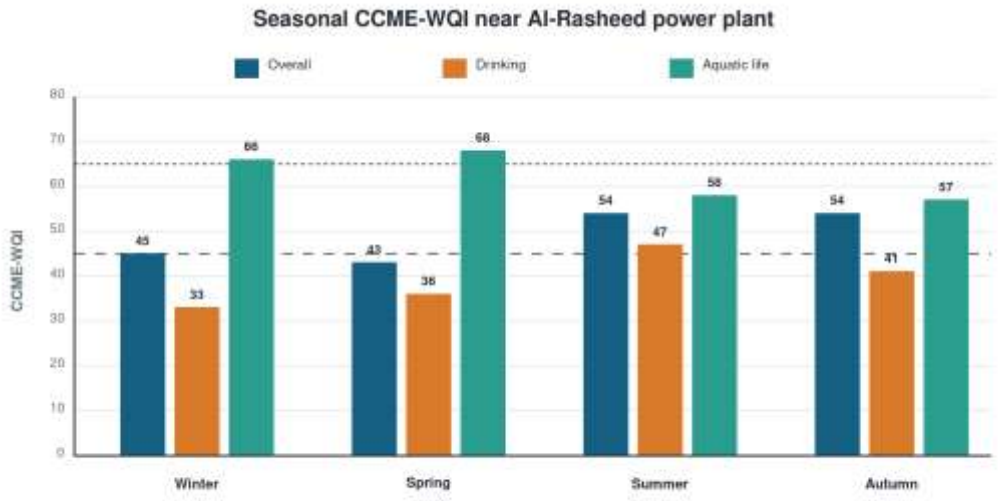


Figure 4. Seasonal CCME-WQI values near Al-Rasheed electrical power plant. Source: Alazawii et al. (2018).

In Baghdad, for instance, treated wastewater from the Rustumiyah and Karkh treatment plants that are directed to the Diyala River travels to the Tigris River through additional natural flow purification processes before being abstracted for irrigation downstream. In Iraq, raw sewage is used to fertilize nonfood crops [44]. However, if treatment does not adhere to national environmental rules, river pollution will rise and crops will get contaminated with heavy metals like lead and cadmium. Aziz and Aws examined various phases of Rustumiyah WWTP's output, including tap water, treated sewage, nontreated sewage, and dried sewage sludge. Despite their advantages as a source of agricultural fertilizers and soil improvement, the results showed that sewage sludge and untreated influent pose potential dangers related to the accumulation of heavy metals and microorganisms. The first stage (heavy solids settlement), which failed to remove total dissolved solids (TDS) and total suspended solids (TSS), had a negative effect on the later phases of treatment, according to a follow-up study by Rasheed [45]. Furthermore, as has been shown in other regions of Iraq, the amount of water entering the plant surpassed its capacity, resulting in the untreated water being thrown directly into the river.

Figure 5 converts the reviewed evidence into a preliminary treatment-screening framework. WQI class is used as an initial indicator, while the final process train must be confirmed against parameter-specific limits, especially salinity, turbidity, organic loading, pathogens, membrane fouling potential, design flow, and population density. Reverse osmosis is therefore proposed only when dissolved-salt removal is required, not solely because a WQI value is low.

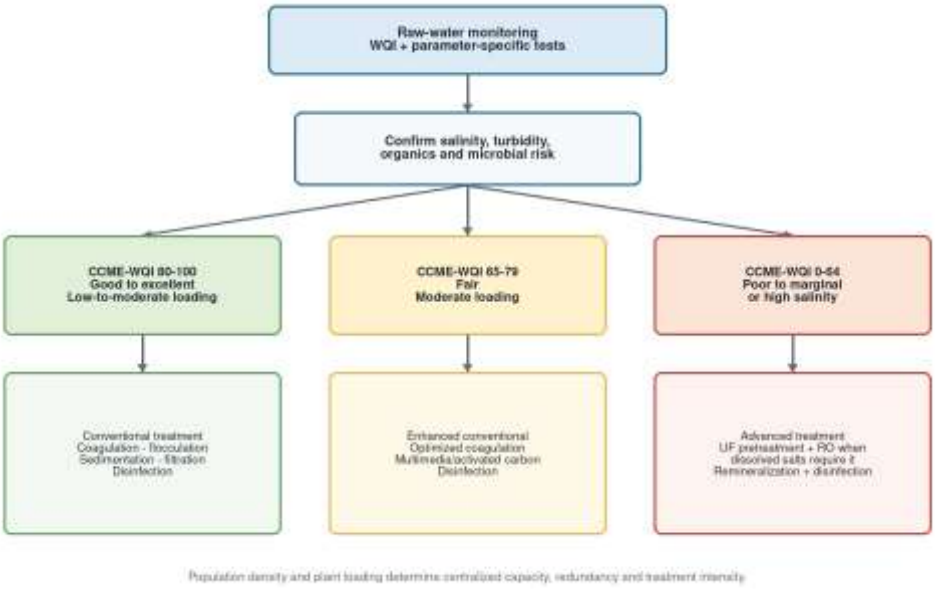


Figure 5. Proposed treatment-screening framework based on CCME-WQI class, parameter-specific risks, and population pressure. Source: Synthesized from Uddin et al. (2021) and the studies reviewed in this paper.

Sludge-drying reed beds seem to be a new and alternative technology with low energy requirements, lower operating and maintenance costs, and minimal environmental impact. Reed beds are an alternative technology WWT system that mimics the biogeochemical processes inherent in natural wetlands [46]. Phragmites australis (common reed) and other emergent rooted wetland plants are planted in shallow tanks filled with a layer of gravel to create sludge-drying reed beds, which have been used in Palestine and Europe. After waste sludge is pumped and deposited on the reed bed surface, most of its water content is lost due to evapotranspiration from the plants and water draining through the gravel filter layer, leaving a concentrated sludge residue on the surface of these systems.

By creating aerobic microsites that support sludge stability and mineralization, the roots of the plants aid in the transfer of oxygen across sludge layers. Furthermore, the complex root structure maintains the drainage efficacy of the bed by protecting the pores and microscopic channels in the sludge layer. The wind-driven movement of plant stems causes surface cracking beds when the sludge is dry, which improves the aeration of the sludge layer. Unlike sludge disposal in landfills or cremation, the finished product is appropriate for land application and may be further treated to improve sludge hygienization. Begg discovered that removal effectiveness for BOD, TSS, and sludge dewatering was greater than 90%. The rates of nitrate and total phosphorus removal were 90% and 80%, respectively.

87% of the metal was removed efficiently. The highest metal levels were frequently found in the lower rung of the sludge profile. TS content rose steadily from 1% to 3% in the influent to 20% to 30% in the beds, which is within the range attained with conventional dewatering techniques, according to Uggetti [47]. Additionally, sludge stabilization in the beds and a gradual elimination of organic matter were observed (volatile solid concentration decreased from 52% to 67% TSS in influent to 3149% TSS in beds). Heavy metal concentrations remained within permissible limits, but the sludge that had developed in the beds had a very high nutritional concentration low (TKN 2–7% TSS and TP 0.04–0.7% TS).

The treatment performance reported for sludge-drying reed beds is summarized in Figure 6. BOD removal, TSS removal, sludge dewatering, and nitrate removal reached at least or approximately 90%, while total phosphorus removal was 80%. These results support reed beds as a low-energy option for sludge management, although land availability and long-term solids

accumulation must be considered in full-scale selection.

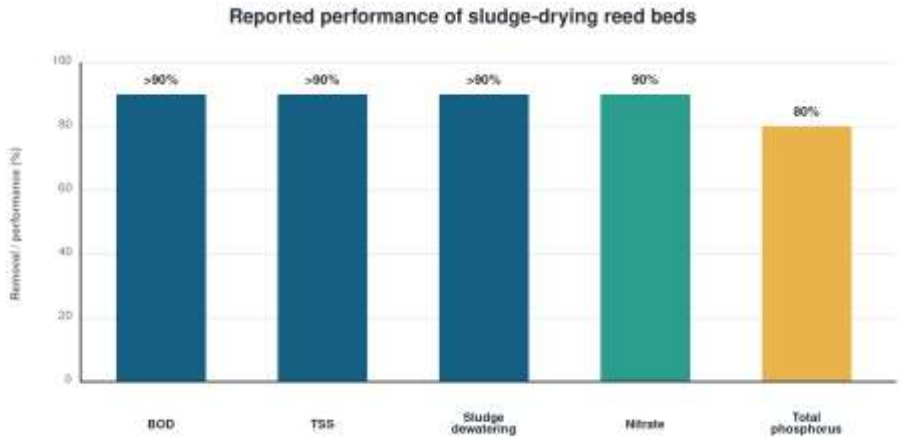


Figure 6. Reported performance of sludge-drying reed beds. Source: Begg et al. (2001).

3. Results

All the reviewed studies show that upstream to downstream, water quality decreases along the Tigris and Euphrates Rivers with the increase of anthropogenic pressures. The general trend was that the physical parameters such as Electrical conductivity (EC), Total Dissolved Solids (TDS), turbidity and salinity values were higher in the southern parts with more population than the northern parts of the country. This is a spatial variation due to the combined effect of municipal wastewater discharge, agricultural runoff, industrial effluents and decreased river flow due to abstraction of the water.

Several sampling sites showed higher levels of nutrients, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and heavy metals (lead, cadmium, chromium, and copper). The most pronounced of these pollutants occurred in the areas around the larger urban areas, demonstrating that population density and industrialization have a significant impact on river water quality. The higher nutrient levels also lead to eutrophication and algal blooms, which further impact on water quality.

Another significant concern is the biological contamination. Many studies reported high levels of total coliforms, fecal coliforms and pathogenic microorganisms in areas where untreated municipal wastewater is discharged. These results help to understand the persistence of the water borne diseases in some provinces of Iraq and the importance of the necessity of wastewater treatment infrastructure and the continuous microbiological monitoring.

The Water Quality Index (WQI) assessments always showed that the water quality in the river was getting worse downstream. Most monitoring stations in the North had “good” to “fair” water quality, while stations in close proximity to high population urban areas often were categorized as “marginal” or “poor”. This example illustrates the value of using WQI as an integrated approach to evaluate river health and the need to apply parameter-specific analysis to choose the best treatment technology.

The treatment technologies reviewed showed that none would be applicable to any and all pollution conditions. For fairly low polluted areas, conventional treatment is still suitable. For areas with high salinity, high organic load, microbial contamination and growing population, more advanced treatment technologies such as membrane filtration and reverse osmosis are necessary. Sludge management and nutrient removal, in particular, also has low energy potential, either by means of sludge drying beds with reeds or other nature-based solutions, where land is available.

The evidence as a whole indicates that there is a clear correlation between population density and water quality degradation in the Tigris and Euphrates Rivers. However, in the context of urbanization, sustainable water resource management should be based on ongoing water quality monitoring, integrated pollution control, increasing the capacity of water treatment plants, and choosing the most appropriate water treatment technologies depending on the nature of the pollutants present in the urban water system, not depending on a single water quality index. Such mutually reinforcing approaches are expected to enhance water security and long-term environmental sustainability in Iraq.

Author & Year	Study Area	Main Findings
Alharbawee et al. (2023)	Tigris River	Water quality declined downstream due to increased pollution loads and population activities.
Hadi & Al-Juhaishi (2023)	Tigris River (Mosul–Al-Amarah)	Northern stations showed better WQI values than southern urban regions.
Ismail et al. (2024)	Tigris and Diyala Rivers	Wastewater discharge and urbanization significantly affected water quality.
Ahmed et al. (2024)	Iraq Rivers	Wastewater treatment infrastructure is insufficient to handle increasing pollution loads.
Oleiwi et al. (2025)	Euphrates River	Salinity and pollution levels increased downstream because of population growth and climate change.

There are many studies that have evaluated water quality of Tigris and Euphrates Rivers, but very few have integrated water properties with population density to establish optimum treatment methods for different areas of Iraq. Most of the previous research focused either on pollution assessment or treatment techniques alone, and did not provide a comprehensive link between the treatment performance and demographic pressure. More studies are required to develop integrated models that integrate population density analysis, sustainable treatment selection, water quality assessment, and enhanced water resource management in Iraq.

4. Discussion

The findings synthesized in this review demonstrate that the deterioration of water quality in the Tigris and Euphrates Rivers is closely associated with the combined effects of population growth, urbanization, agricultural activities, industrial discharge, and declining river flows. A consistent spatial pattern can be observed from northern to southern Iraq, where water quality generally becomes poorer in downstream and densely populated areas. This pattern is supported by the reported CCME-WQI values for the Tigris River, which ranged from 83–94 in Mosul but decreased to 52–59 in Al-Amarah [14]. Similarly, studies conducted in Baghdad and other central and southern regions showed that water-quality indices declined after the rivers passed through urban and industrial areas [9], [13], [41]. These findings indicate that pollution accumulation is not distributed uniformly along the rivers but is strongly influenced by local demographic pressure, wastewater discharge, land use, and hydrological conditions.

The deterioration in physical water characteristics is particularly evident from increasing electrical conductivity, total dissolved solids, turbidity, and salinity toward southern Iraq. High salinity is a major concern in the lower reaches of the river system, especially around Basra and the Shatt Al-Arab, where reduced freshwater discharge allows greater saltwater intrusion from the

Arabian Gulf [10], [11]. This phenomenon is intensified by upstream water abstraction and declining river flow, which reduce the dilution capacity of the river. Therefore, the observed increase in salinity should not be interpreted exclusively as a consequence of population density. Hydrological alteration, natural salt dissolution, irrigation return flows, and seawater intrusion also contribute substantially to the degradation of downstream water quality [19]. This interaction highlights the importance of considering both anthropogenic and natural factors when interpreting spatial differences in river-water characteristics.

Chemical contamination further demonstrates the cumulative pressure imposed on the Tigris and Euphrates Rivers. Elevated concentrations of nutrients, organic matter, and heavy metals have been documented in different Iraqi water bodies [20]–[27]. Increased biochemical oxygen demand and chemical oxygen demand are closely associated with municipal and industrial wastewater inputs, whereas nitrate and phosphate enrichment is strongly influenced by domestic wastewater and agricultural runoff. Excessive nutrient loading may promote eutrophication and algal growth, thereby reducing dissolved oxygen and affecting aquatic ecosystems. Heavy metals such as lead, cadmium, chromium, and copper are of particular concern because they may accumulate in sediments and aquatic organisms and potentially enter the human food chain. These observations reinforce the need for treatment strategies that are selected according to the dominant contaminants rather than relying exclusively on a generalized water-quality classification.

Biological pollution represents an equally significant concern because several studies have associated contaminated Iraqi water supplies with coliform bacteria, pathogenic microorganisms, and outbreaks of waterborne diseases. Reports of hepatitis E, cholera, typhoid fever, parasitic diarrhea, and other gastrointestinal illnesses demonstrate the direct public-health implications of inadequate water and sanitation infrastructure [29], [31]–[34]. The persistence of microbial contamination is particularly important in densely populated areas where wastewater-treatment systems are overloaded or where untreated sewage is discharged directly into rivers. Consequently, improvement of river-water quality requires not only better drinking-water treatment but also effective control of pollution at its source through expanded sewerage networks, improved wastewater-treatment performance, and stricter regulation of untreated effluent discharge.

The reviewed WQI studies provide an effective means of summarizing these spatial and temporal patterns. The decline in WQI values from northern to southern stations supports the general conclusion that river-water quality deteriorates with increasing cumulative human pressure. However, WQI should be interpreted cautiously because different indices use different parameters, weighting systems, and classification criteria [39]. For example, BWQI and CCME-WQI values cannot be directly compared because they are based on different calculation procedures. Furthermore, a single WQI value may conceal important parameter-specific risks. Water classified within the same overall quality category may require very different treatment if the principal problem is microbial contamination, high turbidity, organic loading, heavy metals, or dissolved salts. Therefore, WQI is most useful as an initial screening and communication tool and should be complemented by individual water-quality parameters when selecting treatment technology.

The relationship between population density and river-water degradation identified in this review is substantial but should not be treated as a simple linear relationship. Population density generally increases wastewater generation, solid-waste production, water demand, and pressure on existing treatment infrastructure [35]. Nevertheless, the environmental impact of population growth depends strongly on the availability and performance of sanitation systems. A densely populated city with adequate wastewater treatment may impose less pollution pressure than a smaller community where untreated sewage is discharged directly into the river. Similarly, industrial activity, agricultural drainage, reduced river discharge, and climatic conditions can intensify pollution independently of population size. Population density should therefore be considered as one component of an integrated treatment-selection framework rather than as the sole determinant of treatment requirements.

The treatment technologies reviewed in this study indicate that different levels and types of contamination require different treatment configurations. Conventional treatment processes remain appropriate where turbidity, suspended solids, organic matter, and microbial contamination are within manageable ranges. However, heavily urbanized and downstream areas may require additional treatment barriers when conventional systems cannot adequately address high salinity, dissolved contaminants, pathogens, or industrial pollutants. Membrane-based processes, including reverse osmosis, are particularly relevant where dissolved-salt concentrations exceed acceptable limits. Nevertheless, reverse osmosis should not automatically be selected solely because a water source has a poor WQI. Its application should be justified by parameter-specific evidence, especially high TDS, conductivity, chloride, or salinity, while membrane fouling potential, pretreatment requirements, energy consumption, concentrate disposal, and operating costs must also be considered.

Nature-based technologies such as sludge-drying reed beds provide another useful component of sustainable wastewater management. The reviewed evidence indicates that reed-bed systems can achieve high removal efficiencies for BOD, TSS, nitrate, phosphorus, and several metals while requiring relatively low energy and operational inputs [46], [47]. These characteristics make them particularly attractive for sludge management and decentralized applications where sufficient land is available. However, their applicability in highly populated urban centers may be constrained by land requirements and long-term solids accumulation. Consequently, reed beds should be regarded as complementary technologies rather than universal substitutes for conventional or advanced wastewater-treatment processes.

Overall, the evidence suggests that sustainable management of the Tigris and Euphrates Rivers requires a location-specific and risk-based treatment strategy. Areas with relatively low pollution pressures may continue to rely on optimized conventional treatment, whereas densely populated urban and downstream areas require stronger wastewater control and, where necessary, advanced treatment technologies. Treatment selection should therefore integrate population pressure, WQI classification, individual pollutant concentrations, river-flow conditions, treatment-plant capacity, land availability, and operational feasibility. Such an integrated approach would provide a more scientifically defensible basis for protecting drinking-water supplies, reducing public-health risks, and improving the long-term sustainability of Iraq's freshwater resources.

5. Conclusion

The Tigris and Euphrates Rivers are important sources of water for human beings, but they face serious environmental problems due to population, untreated wastewater discharge, agricultural run-off, industries and climate change. In highly populated places, where traditional treatment systems are frequently inadequate, the deterioration of water quality gets worse. Complex treatment technology may be needed in large urban areas; however, more simple and cost-effective technology may be more suited to a rural area. To guarantee sustainable water quality and public health protection in Iraq, statistical analysis, integrated water management techniques, and ongoing monitoring are crucial.

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