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Climate Change: Droughts and Increasing Desertification in the Middle East, with Special Reference to Iraq

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Abstract

Climate change impacts on Earth's atmosphere have caused drastic changes in the environment of most regions of the world. The Middle East region ranks among the worst affected of these regions. This has taken forms of increasing atmospheric temperatures, intensive heat waves, decreased and erratic precipitation and general decline in water resources; all leading to frequent and longer droughts, desertification and giving rise to intensive and recurrent (SDS). The present conditions have led to increasing emissions of (GHG) in the earth atmosphere. All future projections especially those using (IPCC) models and emission scenarios indicate that the Middle East will undergo appreciable decrease in winter precipitation with increasing temperature until the end of this century both of which are inductive to increased dryness and desertification. Iraq as one of the countries of this region and due to its geographical location, its dependence mostly on surface water resources originating from neighboring countries, long years of neglect and bad land management put it in the most precarious and unstable position among the other countries of the region. Modelling studies have shown that Iraq is suffering now from excessive dryness and droughts, increasing loss of vegetation cover areas, increasing encroachment of sand dunes on agricultural lands, in addition to severe and frequent (SDS). These negative repercussions and their mitigations require solutions not on the local level alone but collective cooperation and work from all the countries of the region.

Keywords

Climate Change, East Mediterranean Region, Aridity Indices, Droughts, Desertification, Sand and Dust Storms (SDS), Green House Gases (GHG), Intergovermental Panel for Climate Change (IPCC)

1. Introduction

A drought is a period when an area or region experiences below-normal precipitation. The lack of adequate precipitation, either rain or snow, can cause reduced soil moisture or groundwater, diminished stream flow, crop damage, and a general water shortage. Droughts are the second-most costly weather events after hurricanes [1] [2].

It is common to speak of Meteorological Droughts as being caused from prolonged weather conditions with the precipitation being lower than usual with impacts manifested in two ways; first, agrometeorological water shortage, when soil moisture decreases to such a level that it becomes insufficient to the vegetation of plants, and; second the hydrological water shortage when after a certain long period of precipitation deficit the water level of surface or groundwater sources falls down to certain defined dangerous level. The inevitable consequences of draughts are negative impacts and damages to economic, social and environmental sectors. Desertification on the other hand refers to a loss of productivity in the landscape which may be driven by a combination of influences, such as deforestation, improper land management or inappropriate agriculture or through prolonged drought.

In the Middle East, in which droughts and desertification are already observed in many of its parts, long spells of dry climate will certainly increase the extent of this desertification and will affect new areas which have been thought immune to it. In the study of the present day prevailing natural and meteorological conditions in the Middle East it is believed that the term "drying up", as a new normal irreversible and permanent climatic pattern, should be used instead of "drought", as a normal and reversible pattern, to determine the current climate change situation in the region. But at the same time concludes that scientific findings emphasize the need for further research in order to identify the modality of climate change in the Middle East [3].

Such argument may sound logical to the common observer, but it cannot be taken at face value without further examination and scrutiny. To the geographers, geologists and anthropologist, the long history of our planet earth shows clear evidence of reversible modality between long spells of ice ages and wet climate and very long spells of droughts accompanied with extensive desertification of large regions of the earth. Citing the Sahara Desert as an example: 12,000 years ago, the only place to live along the eastern Sahara Desert was the Nile Valley but around 10,500 years ago, a sudden burst of monsoon rains over the vast desert transformed the region into habitable land. This climate change turned most of the 3.8 million square mile large Sahara into a savannah-type environment and it happened within a few hundred years only. Conditions, however, reverted to dryness some 5500 years ago to the present warm and less humid conditions [4] [5]. The Arabian Desert (Area: 1,855,470 km^2) which is an integral part of the Middle East is actually an extension of the Sahara Desert and it was subject to the same reversals of climatic conditions and impacts, [6]. History also shows that the fall of one of the oldest world empires in the Middle East can be attributed to long spells of droughts. The mighty Neo-Assyrian Empire is claimed to have fallen due to long spell of drought and failure of harvest for many consecutive seasons in the sixth century BC, (**Figure 1**) [7] [8].

This claim is supported by proxy records of historical changes which had occurred to some rivers and lakes in the region, and derived from geological and anthropogenic studies.

Such trend is marking the Middle East weather at the moment, and it is causing the decline of what is traditionally called the Fertile Crescent and the increased desertification of good part of it, (**Figure 2**) [9] [10].

Such events and other similar ones are certainly related to natural feedbacks due mainly to the internal dynamics of land, oceans and atmosphere interacting activities. The present conditions in the Middle East and elsewhere in the world, however, cannot be explained by natural forcing drives alone. As the interference of man with the natural environment has additionally given rise to new impacts and threats in the form of global warming conditions. The impacts of these anthropogenic activities are most probably irreversible in the near future, and they include beside global warming, which is direct consequence of Co2, and other GHG emissions, other activities such as wide scale deforestation and bad land management practices.

In such a case, it is important, for the Middle East and the other regions of the world to study their changing climatic, demographic and social conditions over long enough past in order to evaluate the present conditions and attempt to project these studies into the future; to try and find the driving causes behind such changes and suggest effective remedies if available.

2. Present Prevailing Climatic Conditions in the Middle East

To investigate future trend of weather conditions in the Middle East, it is important to study first the climatic conditions prevailing now and all the forcing drivers behind them. The Middle East region is influenced by its geographical location that increases the impact of climate change, as most of the region is classified as hyper-arid, semi-arid and arid zones shown in (**Figure 3**) [11].

This map and the aridity marked on it are based on climate phenomenon characterized by shortage of water and defined by what is termed as the Aridity Index (AI), given by:

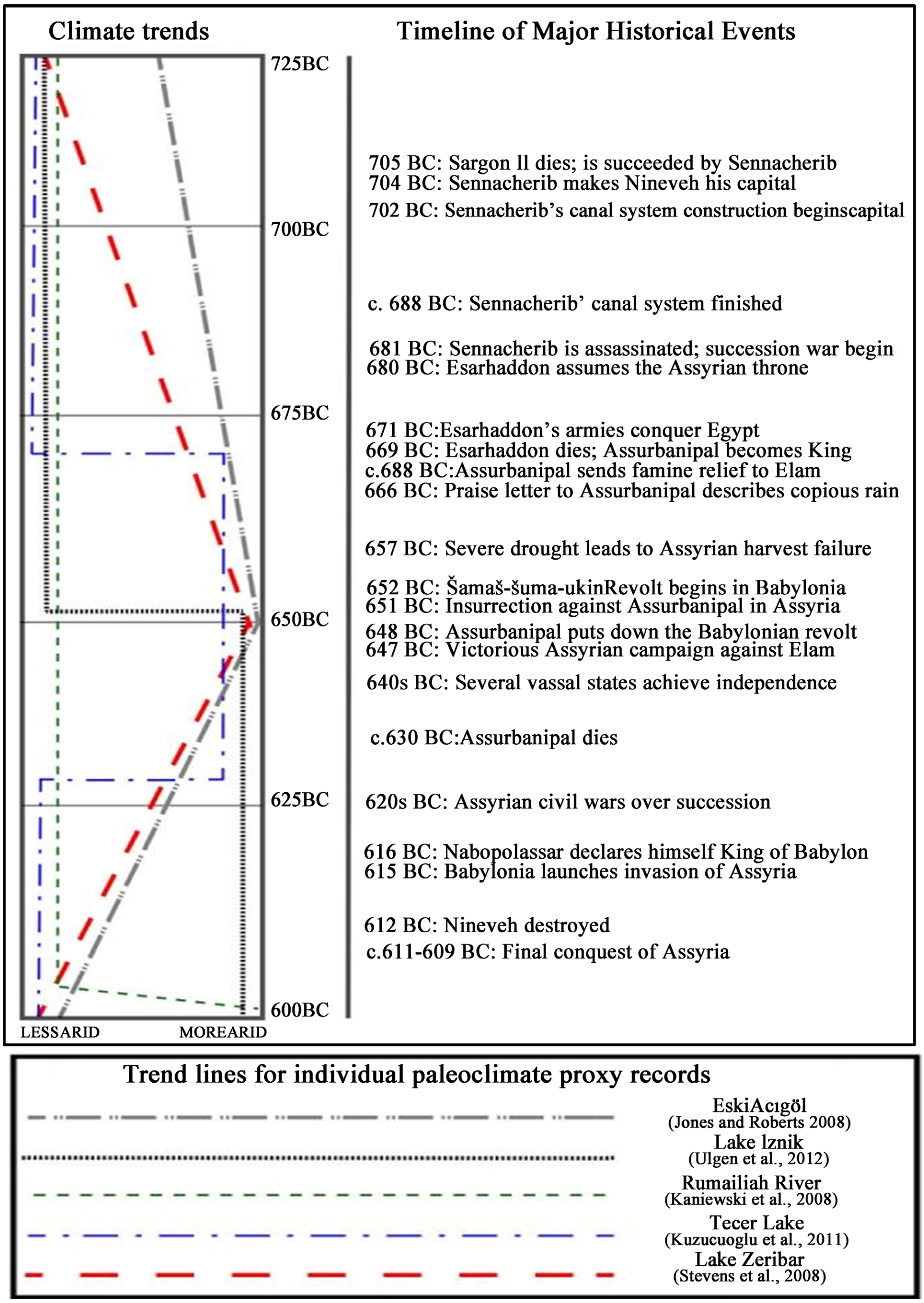

Figure 1. Climate Change trend leading to the fall of the Assyrian Empire: (657 BC.) [7].

$$Al = \frac{\sum_{t-1}^{30}\left(\frac{P_i}{PET_i}\right)}{30} \quad (1)$$

where, P/PET is the ratio of the annual averages of precipitation and potential evapotranspiration, (AI) has been obtained from the observed global distribution of the climate classes over the periods from 1951-1980 and 1981-2010, *i.e.*, computed using the 30-year average of P/PET. According to this classification

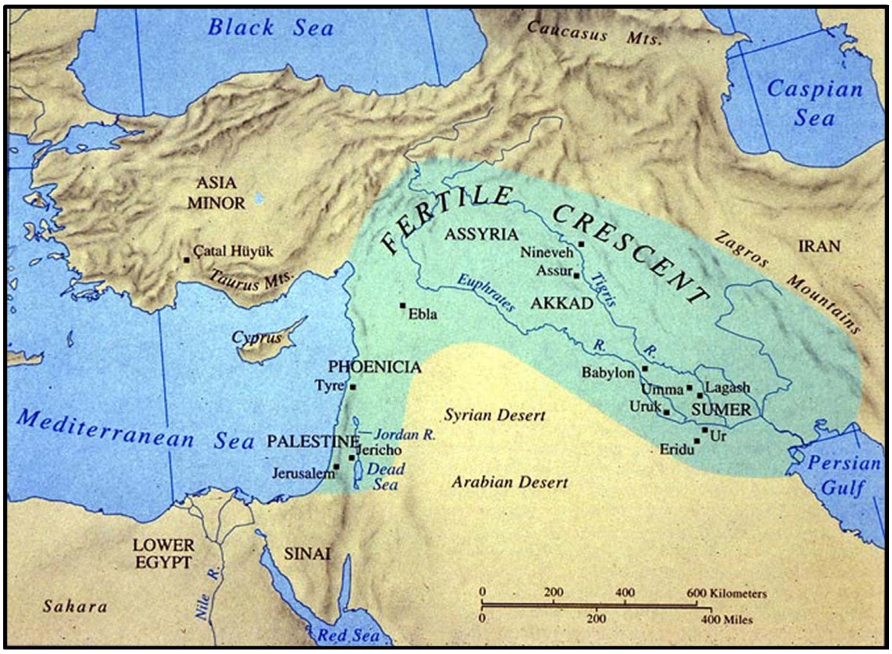

Figure 2. The historic fertile crescent [10]

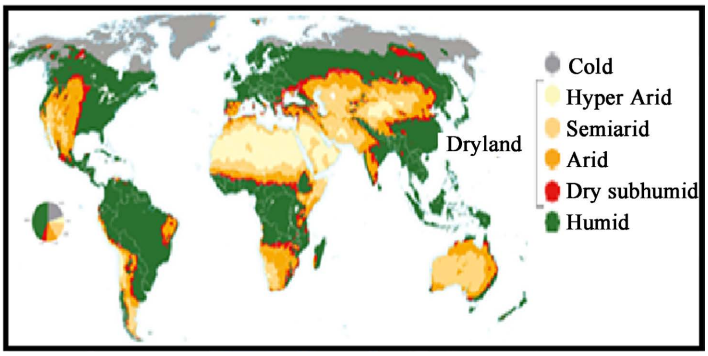

Figure 3. Global distribution of dryland subtypes based on the Aridity Index (in percent of total terrestrial land area) [11].

the Middle East region is either arid or semi-arid, but due to the present trend of global warming the greater part of it is expected to shift from arid and semi-arid conditions shown by (1981-2010) observations to drier arid and hyper Arid conditions in (2071-2100). Accordingly, desertification will spread in southern, middle and western parts of Iraq, Yemen, Jordan and south eastern part of Saudi Arabia, while southern Turkey, great part of Syria, western and northern parts of Iran will move from semi-arid to arid conditions [11].

Most of the precipitation in the Middle East falls or is related to characteristics of the temperate climate region in the northern hemisphere. Summer is almost completely dry, with occasional rainy events triggered by anomalous synoptic conditions Winter precipitation is largely caused by Mediterranean cyclones which are linked to the North Atlantic Oscillation (NAO) and October and May rainfall are results of the Red Sea trough system which can cause intense rainfall and flooding, although it is also responsible for intense sandstorms [12] [13] [14].

The link between the North Atlantic storm and Mediterranean storm tracks has been confirmed by climate modelling studies [15] [16]. Moreover, modelling studies of climate change and associated global warming using different models and scenarios have indicated the shift of the Atlantic storm track northwards and a weakening of the Mediterranean storm track in response to Green House Gases (GHG) emissions. The statistical distribution of storm intensities is virtually preserved under climate change using the (A1B) scenario of the (IPCC) emissions scenarios (SRES) until the end of this century, but there are also indications of a poleward shift and weakening of the Mediterranean storm track, and a strengthening of the storm track north of the British Isles [17]. By using the (IPCC) emission scenarios (A2) and (B2) the results confirm the precipitation change and link it to the change of cyclone activity. The increase of winter cyclone activity in future climate scenarios over western Europe will be responsible for the larger precipitation at the northern coast of the Mediterranean basin, but the bulk of this change is located outside the Mediterranean region. The reduction of cyclone activity inside the Mediterranean region in future scenarios will be responsible for the lower precipitation at the southern and eastern Mediterranean coast which will lead to more dryness over the Middle East and North Africa [18].

3. Expected Trends of Future Climate Change in Middle East

In the prevailing conditions of global warming, mainly resulting from (GHG) increased emissions, all projections especially those using (IPCC) models and emission scenarios indicate that the Middle East will undergo appreciable decrease in winter precipitation with increasing temperature until the end of this century both of which are inducive to increased dryness and desertification. Studies of the history of climate change of this region, which are due to natural drivers alone, suggest reversals of climatic conditions and indicate a future trend of increasing dryness over this region within the foreseen future. This is confirmed by a study of climate conditions during the Early and Mid-Holocene compared to the present-day conditions which was performed using climate change forcing drivers, both natural and anthropogenic, and utilizing idealized simulations coupled to (HadAM3) model and atmospheric general circulation model (GCM). The conclusions were that precipitation in northern Europe, the Mediterranean and the Middle East regions during Early and Mid-Holocene periods (12 k - 8 k), as derived from study of paleoclimate proxies (especially vegetation), was markedly different than it is today, with southern Europe, the Mediterranean and the Middle East being wetter, and northern Europe drier than today. But reversal of conditions of precipitation and temperature was indicated for Europe during (8 k - 6 k). Vegetation reconstruction for Northern Europe suggested colder winters, warmer summers and greater available moisture [19] [20]. This state prevailed up to the beginning of the industrial revolution when an increasing trend for higher temperature, more dryness had begun and was blamed on increased (GHG) emissions of which Co2 from increased burning of fossil fuel was the prime cause [21].

Examination of the prevailing climatic conditions in the Arab region, which is forming the best part of the Middle East for the period (1970-2010) has indicated that long-term trends and natural variability of climate change are related to ((NAO), and that consistent warming trends have been revealed since the middle of the 20th Century. This is evident in the increased frequency of warmer days and nights, higher extreme temperature values, fewer colder days and nights and shorter cold spell durations. The warming trends seem to be particularly strong since the early 1970s. But changes in precipitation patterns, however, seem to have been generally less consistent, and are characterized by a higher spatial and temporal variability; being negative in the eastern part of the region while positive in the western part of it.

In summary, the long term changes in extreme climate indices show that there was significant warming trends all over the Arab region during the period of study (1970-2010) (**Figure 4**), and changes in precipitation indices indicate

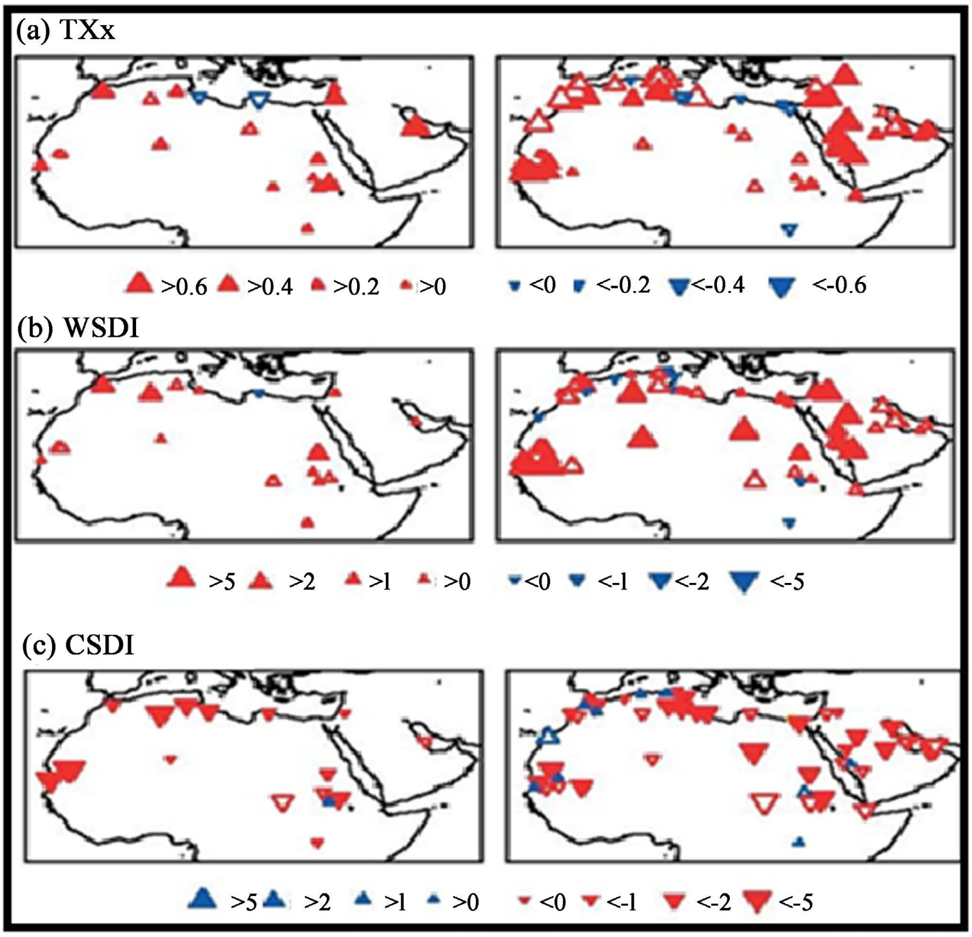

Figure 4. Plots showing annual maximum temperatures (TXx), unit: (˚C/10 years), warm spell durations index (WSDI), unit: (days/10 years), and cold spells duration index (CSDI), unit: (days/10 years). Upward pointing triangles show increasing trends, down pointing triangles represent decreasing trend, significant changes ($p \leq 0.05$) are indicated by filled symbols. Red color coding indicates warming, blue indicate cooling trends [22].

general decrease of total annual precipitation during wet days (PRECEPTOT), and heavy precipitation days of rain of more than 10 mm (R10 mm) over the Arabian peninsula, Iraq, Syria, southern Turkey and western Iran, Egypt, Libya, but a positive trend is observed in Morocco and Mauritania (**Figure 5**) [22].

Unfavorable future trends over the East Mediterranean can be confirmed by deriving the time series of these changes which indicate continuation of the same negative trends in the remaining part of the current century. This is also supported by other modelling studies [23] [24].

4. Droughts and Desertification and the Diminishing Surface Water Resources in Iraq

Iraq is one of the most drought afflicted countries in the world during the last

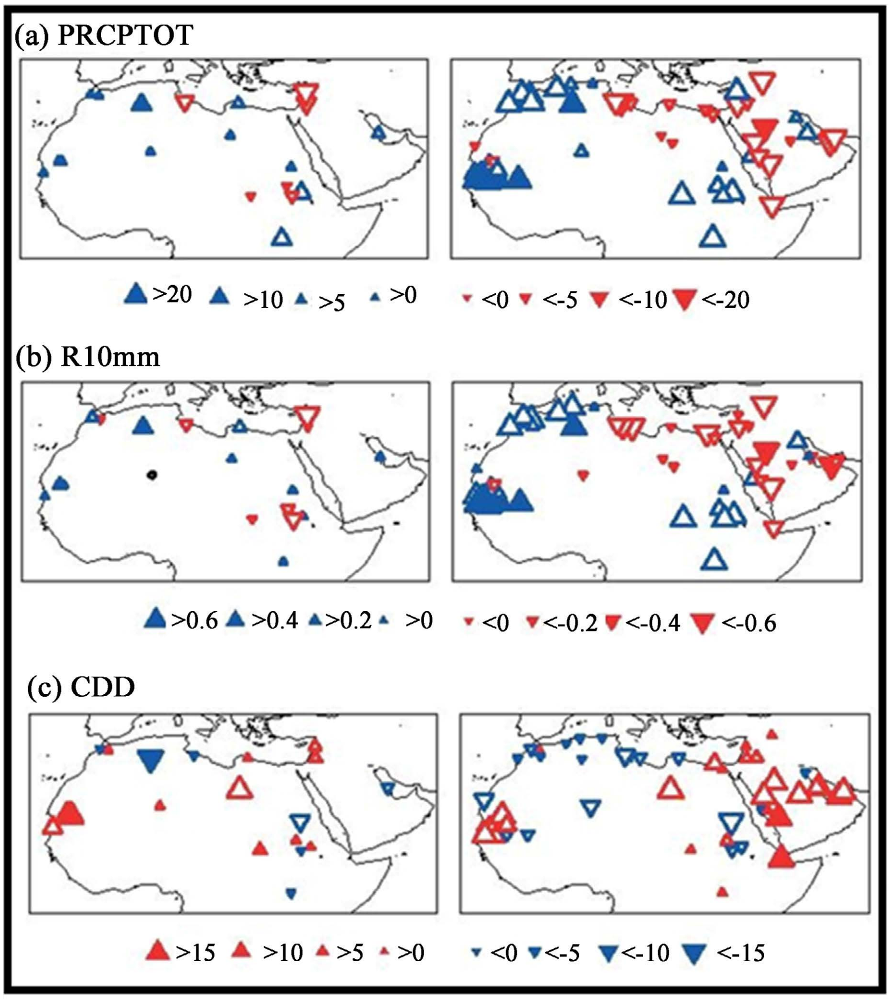

Figure 5. Plots showing annual maximum precipitation indices on wet days (PERCOTOT), unit: mm/10 years, heavy precipitation days (R10 mm), unit: days/10 years and consecutive dry days (CDD), unit: days/10 years. Upward pointing triangles show increasing trends, down pointing triangles represent decreasing trend, Significant changes ($p \leq 0.05$) are indicated by filled symbols. Red color coding indicates warming, blue indicate cooling trends [22].

few decades which resulted from water scarcity and temperature rise. One recent NASA study revealed that the drought that has been affecting the Since autumn 2020, very low levels of rainfall across this region have contributed to drought conditions in both Syria and in Iraq, where large swathes of farmland, fisheries, power production and drinking water sources have been depleted, threatening the lives of millions of people. With temperatures in the Mediterranean basin predicted to increase in the coming years, and water scarcity expected to persist UN reports that extreme climatic events such as extreme drought are likely to "become more frequent and intense" [26]. As a consequence, to this increasing drought in Iraq, desertification has extended over new lands due to lower precipitation rates, reduced natural water resources of the Tigris and Euphrates and ground water depleted supplies, in addition to increasing salinization and abandonment of afflicted areas by farmers. This has contributed to a drop in pasture area and decline of the cultivated land productivity. Consequently, the estimated cultivated lands had decreased from 12.2% to 8.3% of the entire area of the country during the period (1970-2010) [27].

The Tigris and Euphrates rivers originate from catchments which are already suffering from the negative impacts of climate change and decreasing the total annual precipitation over them in south Eastern Anatolia and partly western Iran. This is markedly reflecting in the decline of the mean annual runoff of the two rivers since these areas contribute the largest part of their water resources and causing this is markedly reflecting in declining of their mean annual runoff water stress in Iraq (**Figure 6**) [28].

Long-term analyses of meteorological database (period 1901-2006) together with regional climate change model projections for the 21st century suggest a continued and gradually stronger warming of the area of about (1˚C -3˚C) in the period (2010-2039),and to (3˚C -5˚C) in the period (2040-2069), and (3.5˚C -7˚C) by the end of the century (2070-2099). Analysis of the annual precipitation database for the same period (1901-2006) projections showed a sharp decline of annual precipitation by 5%-30% [29] [30]. Another study employing super-high-resolution atmospheric global climate model (AGCM), that accurately reproduced the precipitation and the stream-flow of the present day "Fertile Crescent" and projected the current trends in climate changes on the Middle East water resources till the end of the century, showed severe reductions of the annual discharges of the rivers in the region. The Euphrates River annual flow, as one case, might suffer a reduction of (29% -73%), as well as the stream flow of the Jordan River, (**Figure 7**) [31].

In another similar study, in terms of the reference period (1961-1990), the outputs of models are indicated in **Figure 8** [32]. This Figure shows the mean annual discharge cycle for Palu, Baağiştas, Hindiya, and Baghdad gauging stations forced, by General Circulation Model's (GCM) outputs and (RCM) outputs for the base period (1961-1990). Projecting to the period (2071-2100) using the (1961-1990) base period, the obtained future mean annual discharge cycle at

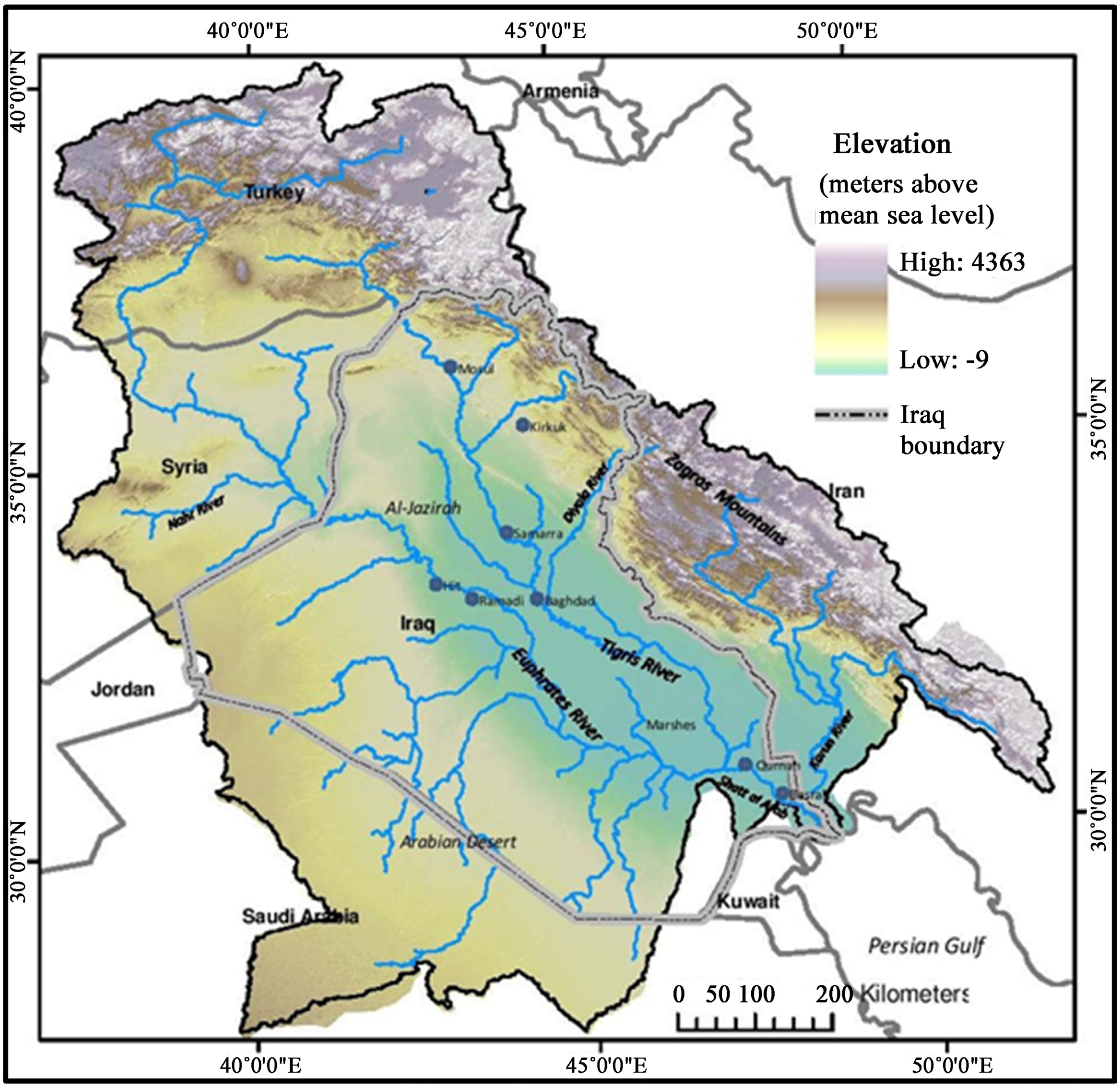

Figure 6. Catchment area of the Tigris and Euphrates rivers [28].

the Palu, Baağiştas (Turkey), and Hindiya (Iraq) gauging stations from the various simulations were obtained and shown in (**Figure 9**). In this figure future mean annual discharge cycle at the Palu, Baağiştas, and Hindiya gauging stations obtained from the various simulations show striking decrease in the mean annual discharge for the Euphrates and Tigris rivers by the end of the current century, ranging from (19%) to (58%), according to the various models used. These results, even with a certain margin of uncertainty, resulting from the uncertainties embedded in the (GCMs) models, mean that any future planning within this basin must be treated with caution and prudence, [32], and that present day progressive decline of water resources in Iraq warrants immediate governmental actions to alleviate the situation.

Notwithstanding the variations in the outputs of the various modeling studies; which reflect different approaches and emission scenarios and different accuracies of input data, all results exhibit indications of increasing temperatures, lower

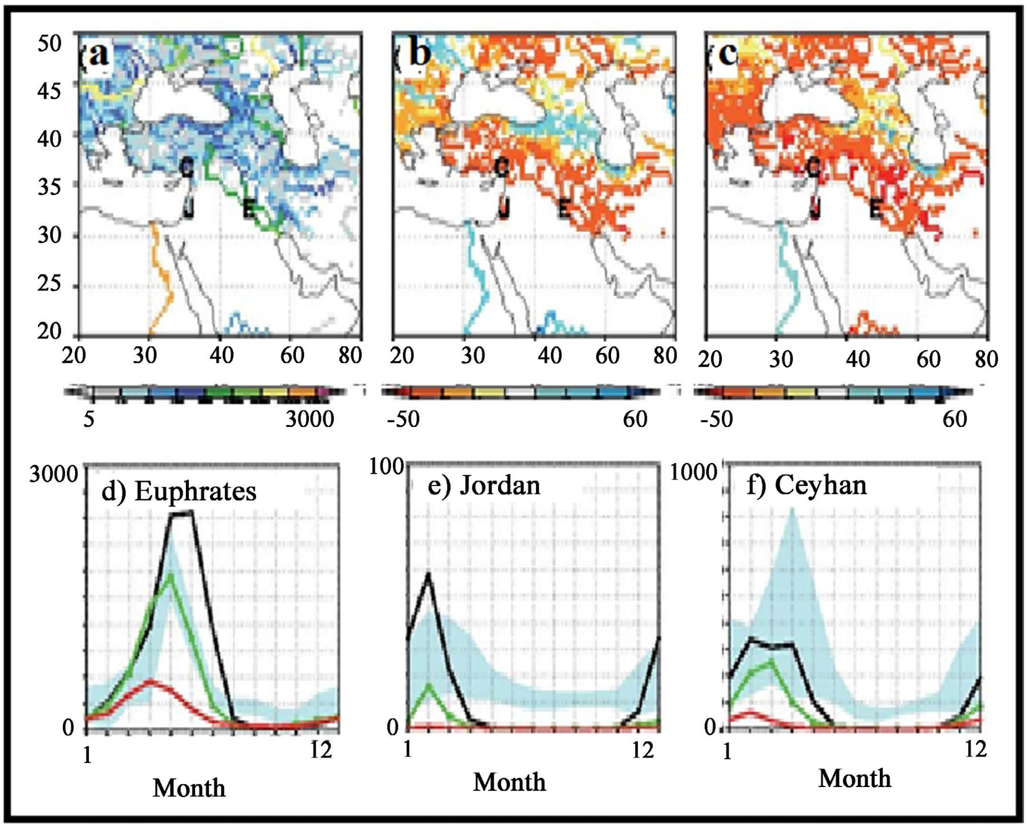

Figure 7. Plots (a)-(c) Annual streamflow simulation results. Plots (d)-(f) give the monthly hydrographs for the Euphrates, Jordan, Ceyhan rivers obtained from (AGCM). In these plots the black line gives (ABCM) present-day monthly streamflows, Green line shows future monthly streamflows scenario (FM) and Red line indicates the same under scenario (FH) [31].

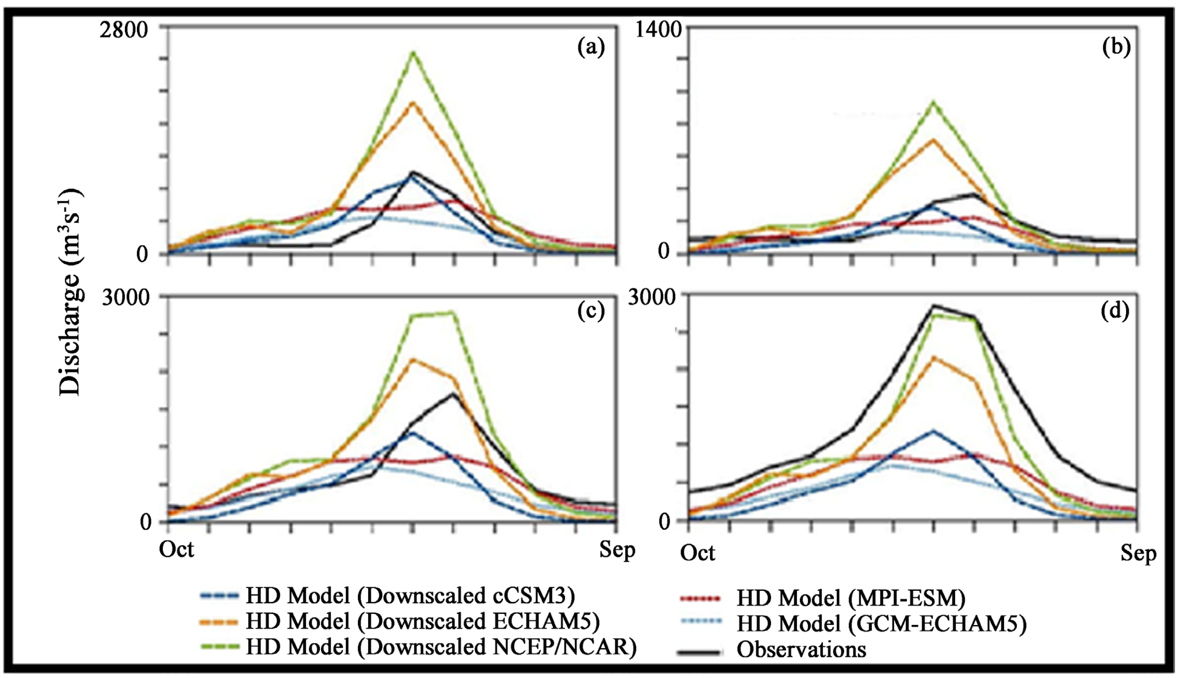

Figure 8. Mean monthly discharge for (a) Palu, (b) Baağiştas¸, (c) Hindiya and (d) Baghdad stream flow gauging station (black continuous line) and the HD model simulation results (dashed lines) forced by GCM-ECHAM5 (blue), MPI-ESM (red RCM-NCEP/NCAR (orange), RCM-ECHAM5 (green) and RCM-CCSM3 (dark blue). Note differences in y-axis scales (1961-1990) [32].

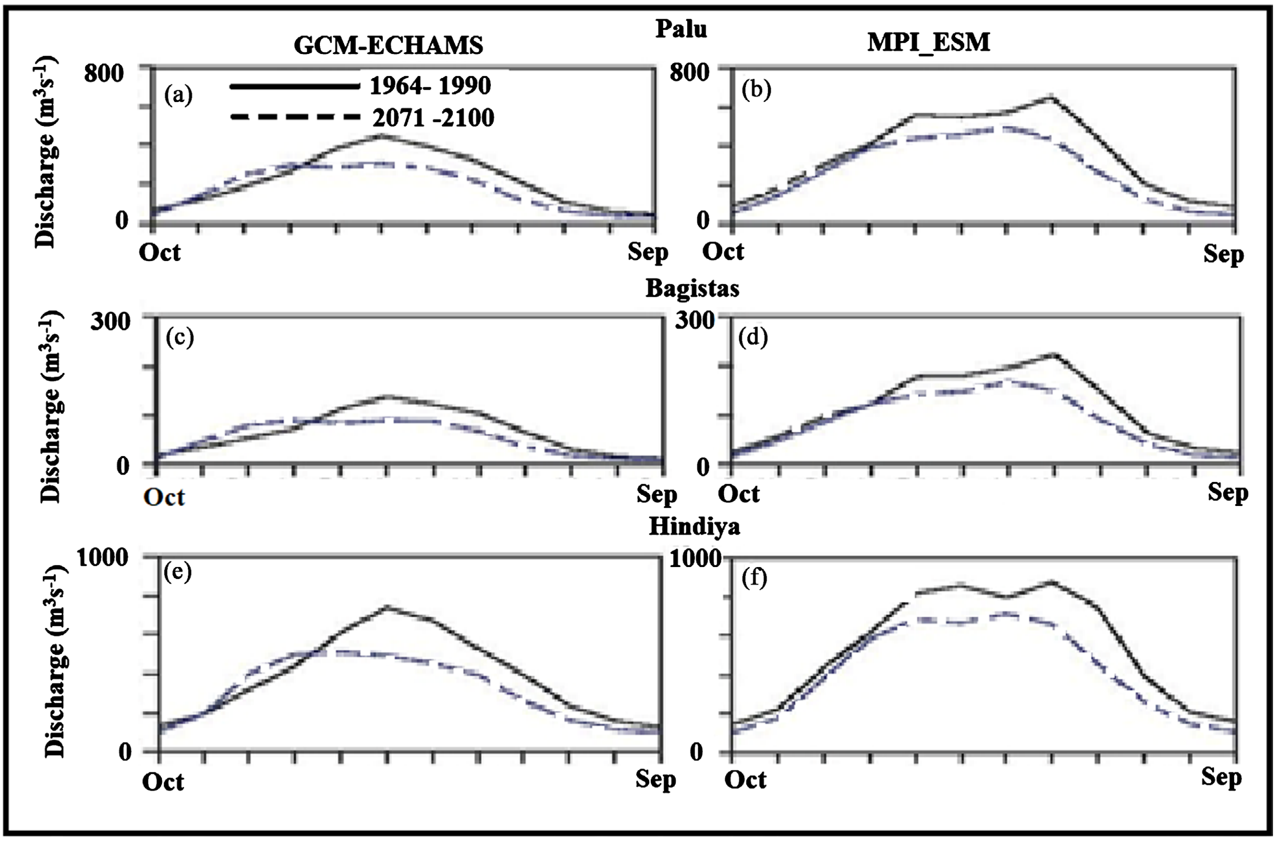

Figure 9. Mean monthly discharge (m^3/s) simulated by the HD model for (a), (b) Palu, (c), (d) Baağiştas¸ and (e), (f) Hindiya for the reference (black solid line) and future (blue dashed line) periods. Forcing-(a), (c), (e) GCM-ECHAM5; (b), (d), (f) MPI-ESM. (base period 1969-1990, future period 2071-2100) [32].

precipitation rates and reduced main rivers' runoffs in the future with extended periods of droughts and increased desertification over large parts of Iraq and the Middle East. Moreover, a trend towards increasing drought frequencies under both the (IPCC) (A2) and (B2) scenarios with a statistical significance of (75%) and (69%), underlines the high vulnerability of the East Mediterranean Region to the negative impacts of climate change. Climate change also has comparably stronger impact on the frequency of drought than on anthropogenic water uses. Water abstractions can, however, intensify drought conditions, [32].

In an important forecast there are indications that today's 100-year drought can occur 10 times more frequently in the future over large parts of the East Mediterranean, while in the western part of North Africa (Morocco and Mauritania), today's 100-year drought will occur less frequently [33].

5. Dryland Changes due to Increasing Temperature in Iraq

In Iraq, climate change has resulted in prolonged heat waves, erratic precipitation, higher than average maximum temperatures and increased disaster intensity, which all are going to worsen in the future, [34] [35] [36] [37] [38]. One report warns that; "in southern Iraq, you have an environment that has been damaged by years of conflict, poor environmental management and weak governance.

When you add climate change into the mix, you have the perfect storm", [39]. In another report it is stated that Iraq among another 11 countries in the world are likely to face excessive warming temperatures, more extreme weather that will threaten their energy, food, water, and health security. Intensifying and more frequent heat waves and droughts will create water supply volatility and probably strain their electric utility operations, while growing economies and populations will increase electricity demands to handle rising temperatures, [40].

Dryland conditions in Iraq have already deteriorated due to the negative trends of climate change. Climate classification map showing dryland conditions of Iraq, together with all other countries of the world, during the period (1980-2016), and projected to (2071-2100) has been derived and compiled from various datasets and climate change scenarios in Köppen-Geiger Climate Classification maps [41]. Dryland conditions maps of Iraq were extracted by the writer from this map for the period (1980-2016) and (2071-2100) and are shown in (**Figure 10(1)** & **Figure 10(2)**). These two maps show clear shifting to hotter and more severe dryland conditions at the end of the 21st century.

6. Decreasing Total Water Surface Area in Iraq

Over 70% of the global net permanent water loss is concentrated in only five countries of the world; namely: Iran, Afghanistan, Iraq, Kazakhstan and Uzbekistan. Observed in 2015, Iran, Afghanistan, and Iraq seem to have lost 56%, 54% and 34%% of their permanent surface water respectively over three decades (**Figure 11**). Climate change and the associated recuring droughts are responsible for part of this loss, but further problems are caused by factors including unregulated water withdrawals, the construction of dams that change flow rate and direction of rivers and misuse of water. The observed loss and use of surface water raises serious concerns for these countries on questions related to water security

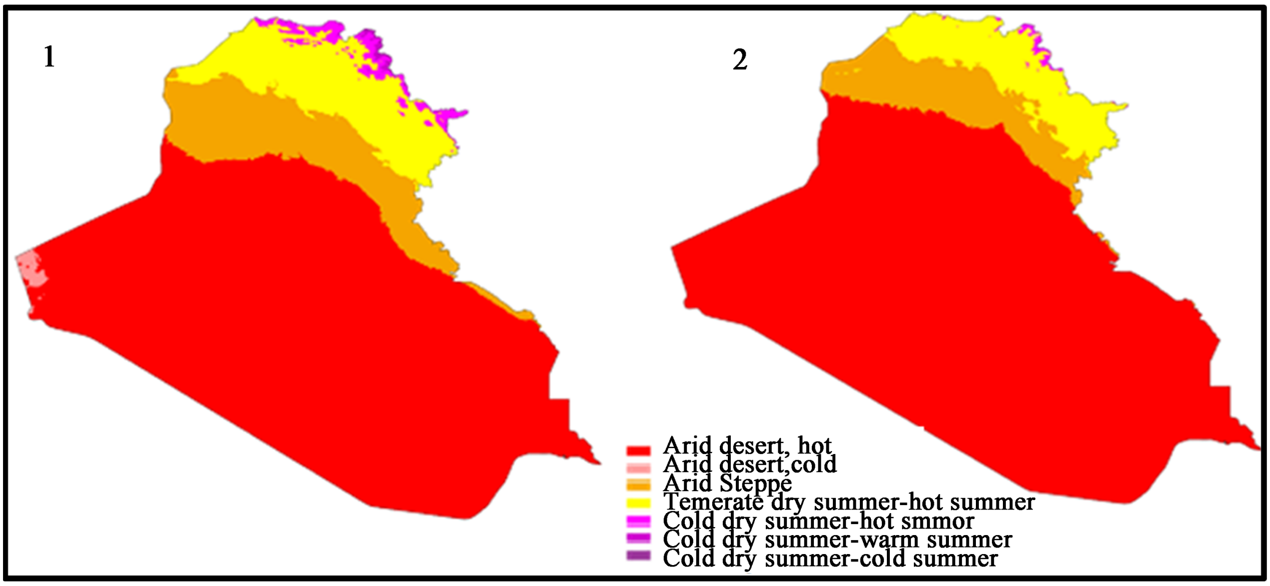

Figure 10. Köppen-Geiger Climate Classification map for Iraq: (1) for (1980-2016), (2) for (2071-2100) [41].

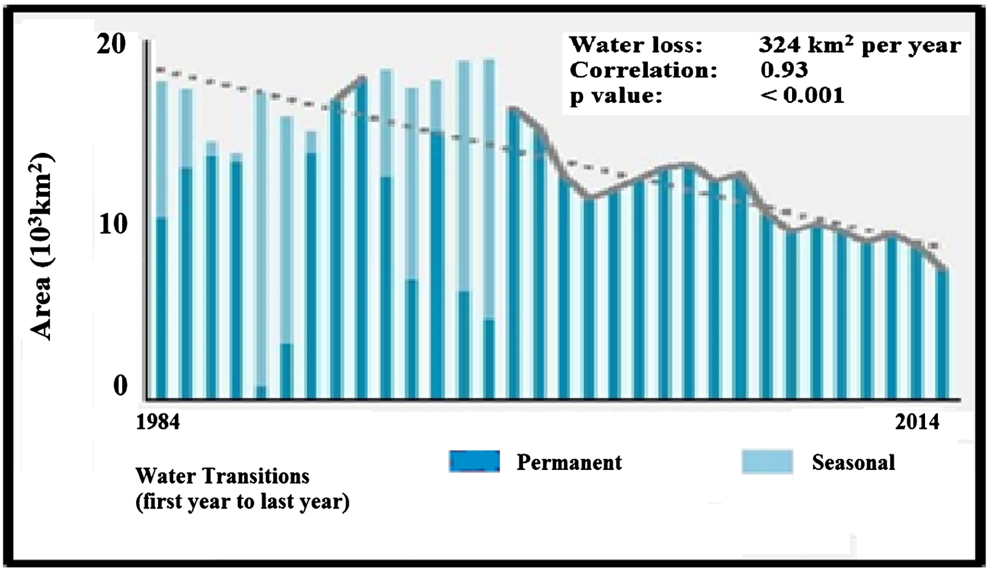

Figure 11. Average annual loss of water surface in Iran, Afghanistan, Kazakhstan and Uzbekistan (1984-2015) [42].

and transboundary water management, as well as sustainability of agricultural productions and food security [42].

In Iraq reduction of water surface area is attributed to climate change impacts of increasing drought conditions as equally as to anthropogenic reasons such as the inequitable sharing of the Euphrates-Tigris water resources with Turkey, Iran, and to lesser degree Syria. Building large dams and Irrigation projects in these countries has resulted in diverting considerable amounts of water. In addition to wasteful use of water in agriculture, drought conditions, however, take a prominent place among the other reasons.

Iraq owns many natural lakes and artificial reservoirs such as the southern marshes which have been very often referred to as the (Gardens of Eden) due to their natural beauty and biodiversity and considered to have been the cradle of Western Civilization. Before the 1990s these marshes; Al-Hawizeh, the Central Marshes and Al-Hammar, shown as site 1), site 2) and site 3) in (**Figure 12**) had covered an area of more than 15000 km^2, but they were drained to 10% of their original size due to political conflicts, and the diversion of Karkheh River by Iran [43].

After 2003 these marshes have partially recovered but drought along with upstream dam construction and operation hindered this process. The 2007-2008 winter season was one of the worst droughts on record, and according to (UNEP) the drought was indeed very serious, [44]. By analyzing the Normalized Difference Vegetation Index (NDVI) and considering three time periods: (1982-1992), (1993-2003), and (2004-2017), the relationships between various water cycles in these marshes were examined through the investigation of vegetation and water coverage changes which was supported by ground observation and statistical analyses over the last 36 years. This has shown significant deterioration of the green biomass which declined by; 68.78% (Al-Hammar Marsh),

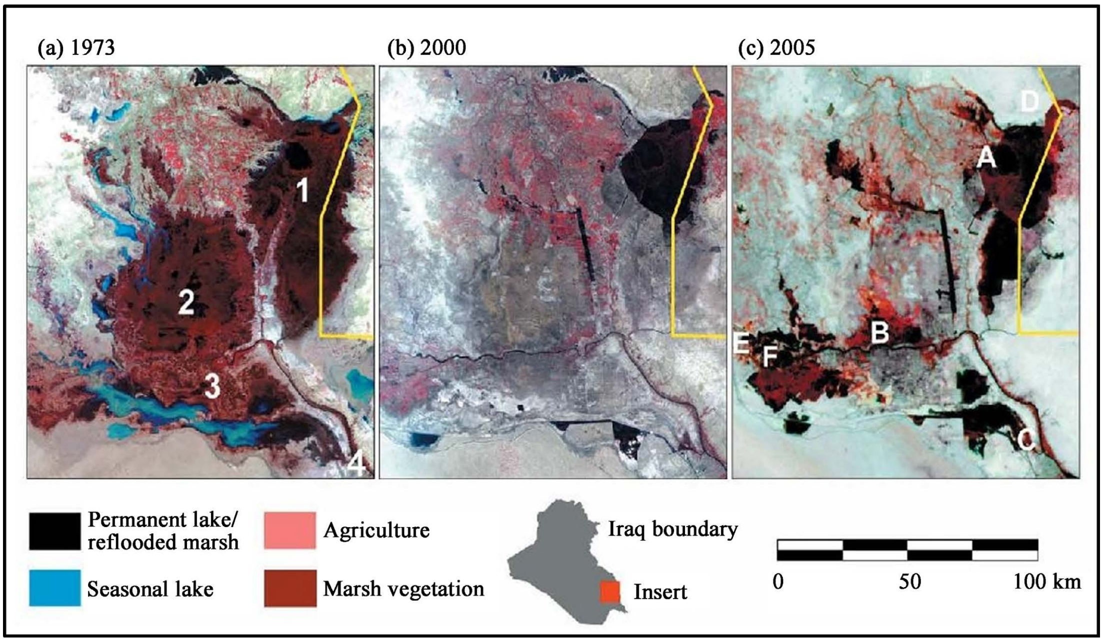

Figure 12. A compositive view of Iraq's southern marshes derived from Landsat 1, and Landsat 7 images [43].

98.73% (The Central Marshes), and 83.71% (Al-Hawizeh) respectively. Droughts and reduction of Tigris and Euphrates river discharges by the riparian countries; Turkey, Syria, and Iran had sharp impacts on water levels. The annual discharge of the Tigris declined from ~2500 - 3000 m^3/s to ~500 m^3/s, and the annual discharge of the Euphrates River declined from ~1500 m^3/s to less than 500 m^3/s [45]. The worsening climatic conditions which exhibited extreme heatwaves and low rainfall caused large parts of these fragile wetlands to turn into places so hostile that the communities who've lived here for generations found it impossible to remain, [46]. Another study using satellite imagery revealed that an increase of surface area of the marshes by (50% - 90%) towards 2020 as compared with that in 2003, but this was only due to intentional reflooding by the government to sustain the marshes as a place of world heritage at the cost of depriving other agricultural lands from their proper share. The results also indicate that the decreased percentage of water surface area during (1972-2000) was (79%) while the increased percentage during (2000-2020) was about (90%) [47]. In our opinion these two studies while giving good indications of anthropogenic drivers of water surface area changes fail in accounting for climate change impacts which have also played a decisive role in this question. It is believed that the Iraqi marshes, which form the largest wetland area in the Middle East and of size more than twice the area of Lebanon, if they dry up to (90%) of their original area, then this is going to produce one of the biggest environmental disaster in the world [48].

Other natural water bodies in Iraq are also diminishing. One striking example, which has suffered this fate solely because of climate change, can be cited from the case of Sawa lake 23 km to the west of Al-Samawah town (**Figure 13**), [49]. The lake is unique, as it is characterized by its highest salinity among the other

Iraqi inland bodies of water. Chemical and isotope analyses revealed its meteoric origin, and its main feeding is from the artesian groundwater coming through its bottom via joints, cracks, and fissure systems. The water level in the lake is higher than the adjacent land around it by (1 - 4) meters, and also higher than the water level of the Euphrates River which flows close to it by (5 - 7) meters. Natural dikes of gypsum are surrounding the lake, and in some cases these dikes reach (6) m height, and they work to prevent water flow from the lake into the surrounding areas. They are formed due to evaporation of salty water and sedimentation of salt in its shallow banks. The lake has been designated as a protected Ramsar site since 2014 [50].

During the last few years, the lake has shrunk to a small fraction of its original area as shown in the photographs of (**Figure 14(1)** & **Figure 14(2)**) [51]. This due to intense heat waves resulting in sharp increase in temperature and evaporation, in addition to excessive withdrawal of water from the numerous wells

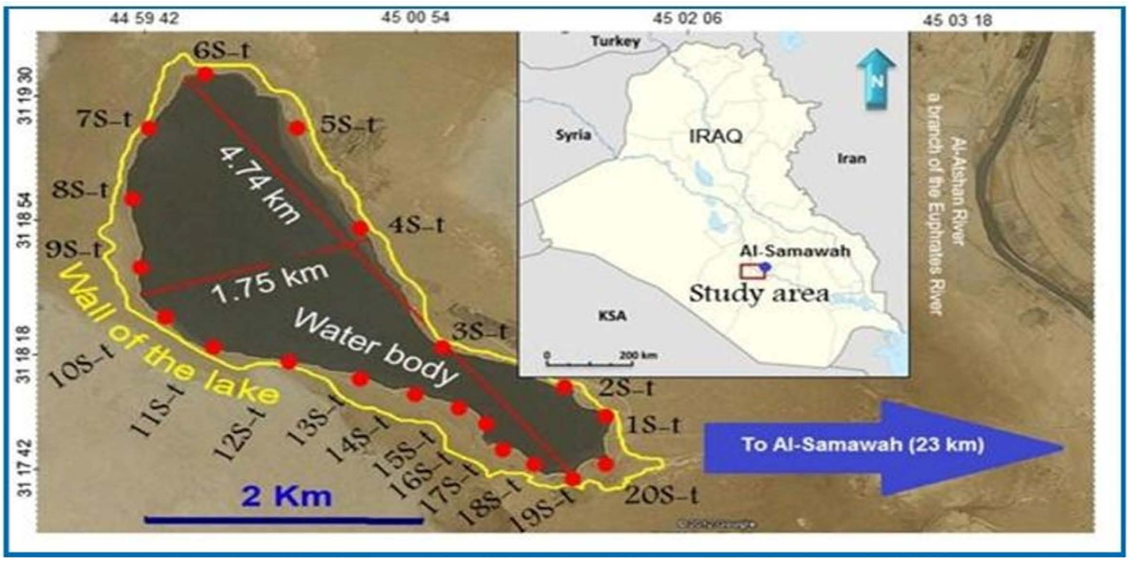

Figure 13. Sawa Lake location map and details [49].

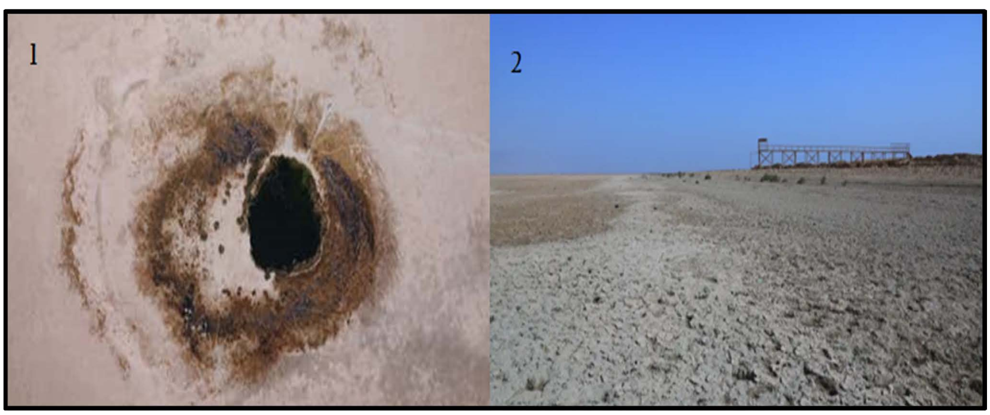

Figure 14. (1) Aerial photograph of Lake Sawa exhibiting present size as contrasted to its original size visible from change in color, (2) view of the lake on April 26, 2022. (Arshad Mohammed/Anadolu Agency via Getty Images) [51].

used by the farmers in adjacent farms who themselves are suffering from water stress due to droughts.

7. Degradation of Vegetation Cover in Iraq

Desertification and drying up of land can be traced by decreasing vegetation cover in many parts of Iraq by using the "Normalized Difference Vegetation Index (NDVI)". This is derived from analysis of satellite imagery by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs) [52]. Another important way to evaluate land degradation is by using the Crust Index (CI) which utilizes the phycobilin pigment found in cyanobacterial soil crusts, resulting in a relatively higher reflectance in the blue spectral region compared to soil without cyanobacteria [53]. Many studies have been done using these indices to evaluate the progression of desertification in various areas of Iraq [54] [55]. One such study covered an area in the middle part of Iraq around Al-Suwaira, Al-Mahawil, Al-Musayab districts and used both of these two indices applying them to two Landsat ETM+ and OLI satellite images from the years 1990 and 2019 shown in (**Figure 15**) [55].

The results showed that the total area of vegetation cover of 2620 km^2 in 1990 decreased by 764 km^2 in 2019. Out of this area 34.8% indicated medium desertification and 10.2% of high desertification (**Figure 16**). Other results revealed important progressive encroachment of sand dunes on the area (**Figure 17**). The 767 km^2 area of these dunes that existed in 1990 increased to 1723 km^2 in 2019. Out of this 10.2% showed (medium desertification) and 22.9% (severe desertification) respectively. The noted overall rate of decrease in vegetation cover in this area was 21.33 km^2/year, while the rate of increased land erosion in the area was 10.99% km^2/year [55].

Even the mountainous region in Iraq which is characterized by the presence of

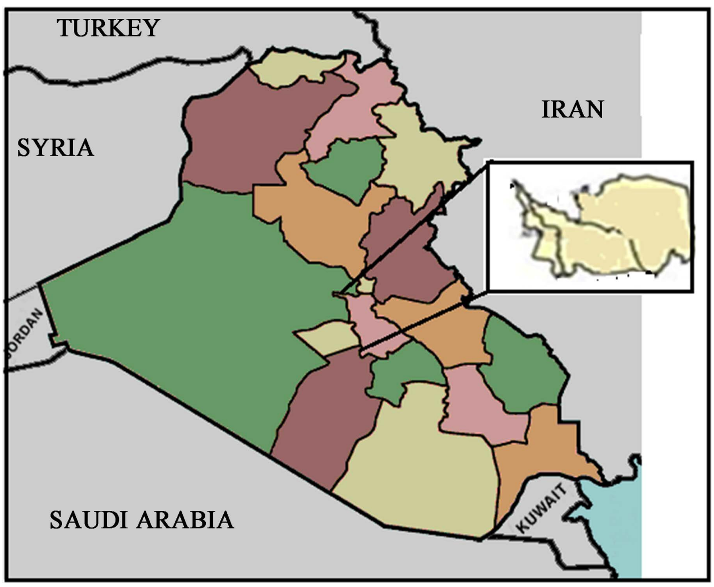

Figure 15. Location map of study area [55].

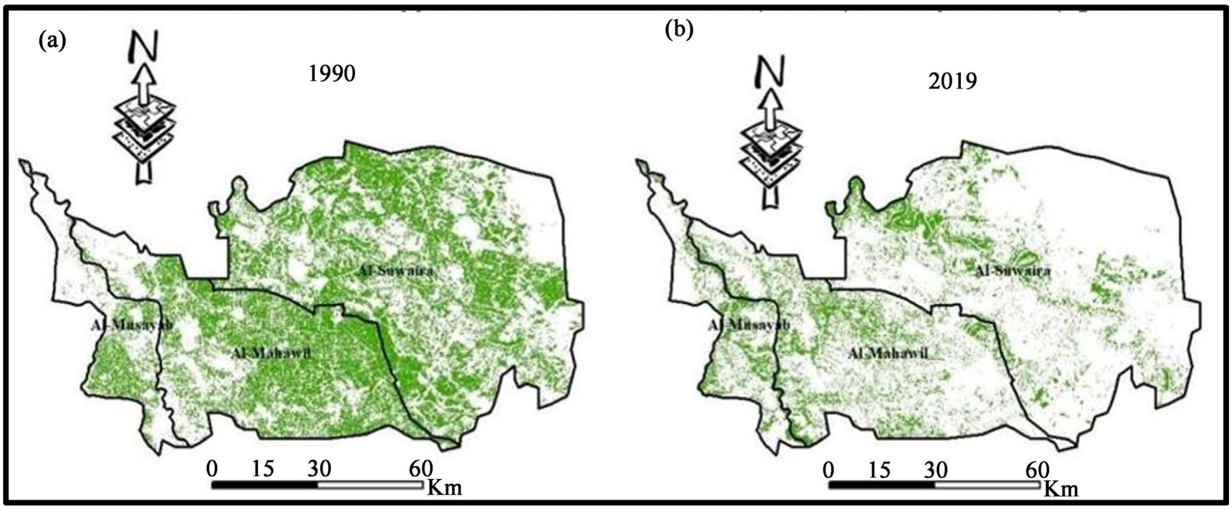

Figure 16. (a) The vegetation cover of study area in 1990, compared to (b) the vegetation cover in 2019 [55].

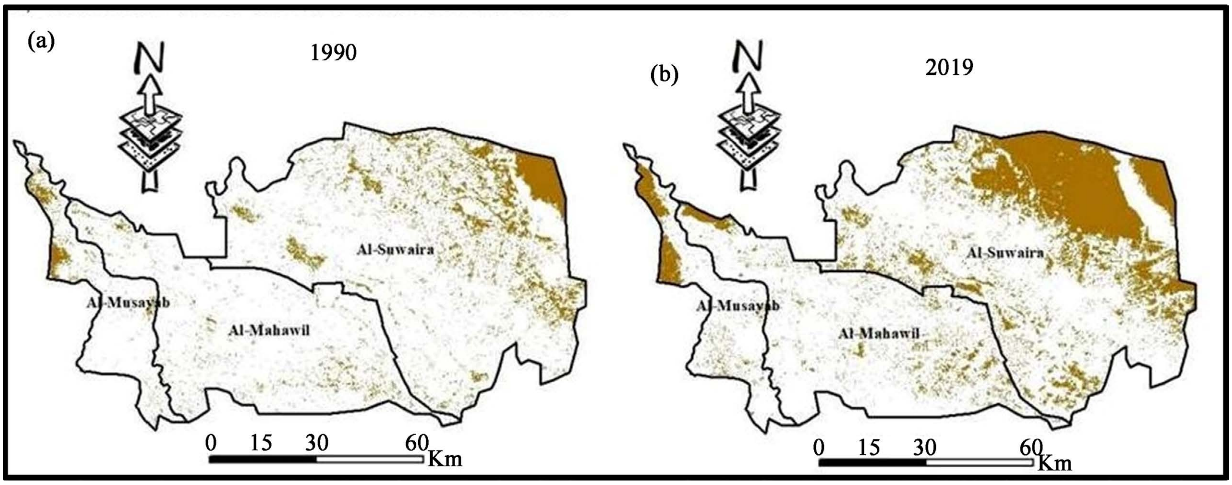

Figure 17. (a) Sand drifting areas in1990, compared to (b) the sand drifting areas in 2019 [55].

natural forests and rangelands suffered from several problems that can be attributed to natural and anthropogenic causes ranging between urban expansion and the decrease in rainfall. Agricultural droughts were clearly indicated in this area as the main reason of this change, [56]. This was confirmed by a study carried out in 2014 which employed Landsat image from 2013. The Normalized Difference Vegetation Index was derived and it was concluded that the forest in the study area had suffered fluctuations during (1984-2015) due to human pressures which caused their degradation, but likewise, climate-related factors have also affected markedly these forests. Iraq in similar ways as other countries in the Middle East has suffered from these factors as maximum temperatures had risen while rainfall decreased to nearly half of its average annual value during the last three decades [57].

8. Increasing Sand Dunes Affected Areas in Iraq

The most important climatic factors affecting desertification and the formation of sand dunes are temperature, evaporation, wind speed and rainfall. Changes in precipitation and rise of temperature have been experienced all over Iraq in recent years in response to climate change. The average annual precipitation all over Iraq has decreased by about 10 mm from 2003 to 2016, with varying degrees over different geographical locations in the country (**Figure 18**) [58].

For the period 1951 to 2000, the nearest station precipitation records for the northeast of Iraq show an increase of 2.4 mm/month per century, while the nearest station records for the southeast indicate a decline of only 0.88 mm/month per century. The nearest station record to the west indicates a decline of 5.93 mm/month per century. Precipitation in Iraq is seasonal and occurs mostly in winter during December through February for most of the country except in the north and northeast, where the rainy season is from November to April; [59]. The climate is also influenced by South and Southeasterly Sharji winds, which are dry dust winds that impact the country from April to June and September to November. The North, Northwest Shamal Winds also impact the climate, leading to extensive surface heating [60]. Temperature measurements records show that mean annual temperatures have risen across Iraq since the 1950s at a rate of 0.7˚C per century, but this value however has soared from 21.87˚C to 23.13˚C during the period from (1901) to (2020). A clear fingerprint of this climate change impact in Iraq is given in (**Figure 19**) [61].

These negative trends together with changes in wind circulation modes across the Middle East, Arabia and over the Red Sea are working together to increase the sand dune phenomenon in the country especially in the absence of any meaningful governmental or communal efforts to combat desertification and decrease the encroachment of sand dunes on new lands. Although a great deal of research work has been performed in the last few years on the formation of sand dunes in various parts of the world [62] [63] [64], not much can be found done on this phenomenon in Iraq when it comes to linking it with climate change impacts.

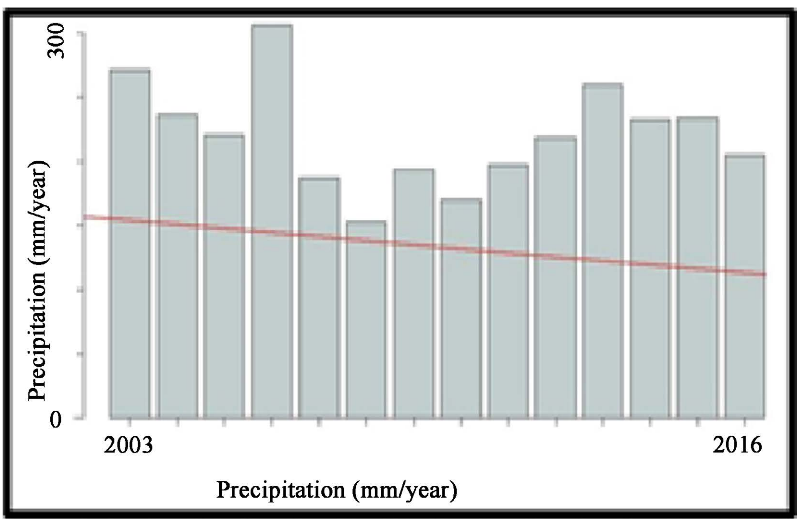

Figure 18. Histogram of the mean annual rainfall pattern for entire Iraq for the period (2003-2015) [58].

One of such studies was published in 2013, covering the period from 1988 to 2009 and deals with the encroachment of sand dunes in the northern middle part of Iraq and covers six districts, namely; Baiji, Al-Daur, Tikrit, Tooz, Al-Khalis, and Kifri; (Figure 20) with a total area of 20,454.70 km^2. The mean annual rainfall in this area ranges between 150 to 250 mm, occurring in winter and spring seasons. The study was based on using only two Landsat images; the first was from Landsat-4 TM image of 20th July 1988, and the second from Landsat-5 TM on 22nd July 2009 and opted for using the normalized difference vegetation cover (NDVI) as an indicator for measuring land degradation level. The obtained results revealed that the area of vegetation cover in most of the studied area in 2009 had decreased in varying degrees from that of 1988. The biggest decreased percentage was 97.7% which occurred in the Baiji district, while the lowest decrease was 2.4% and took place in the Tikrit district. On the

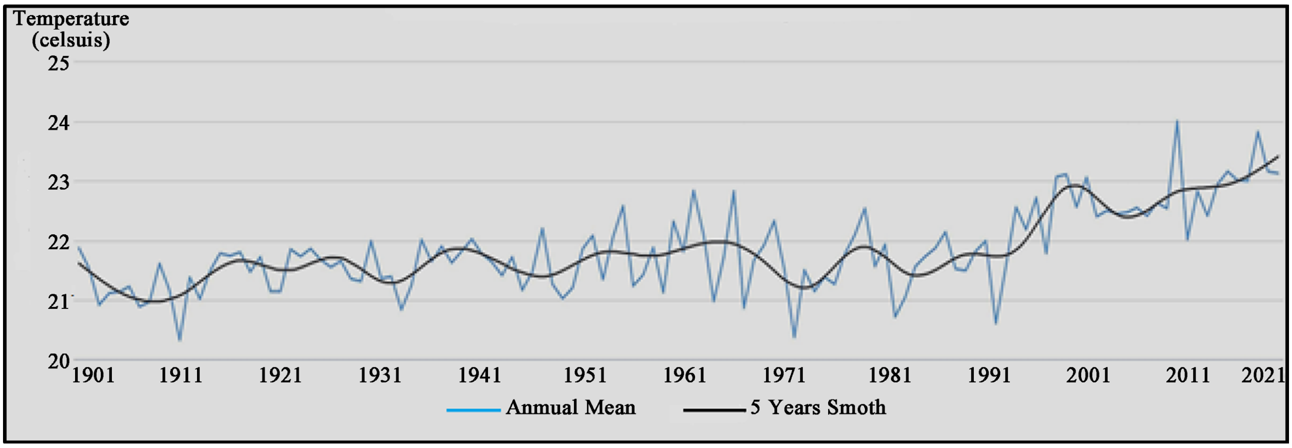

Figure 19. Observed average annual mean temperature of Iraq 1901-2020 [61].

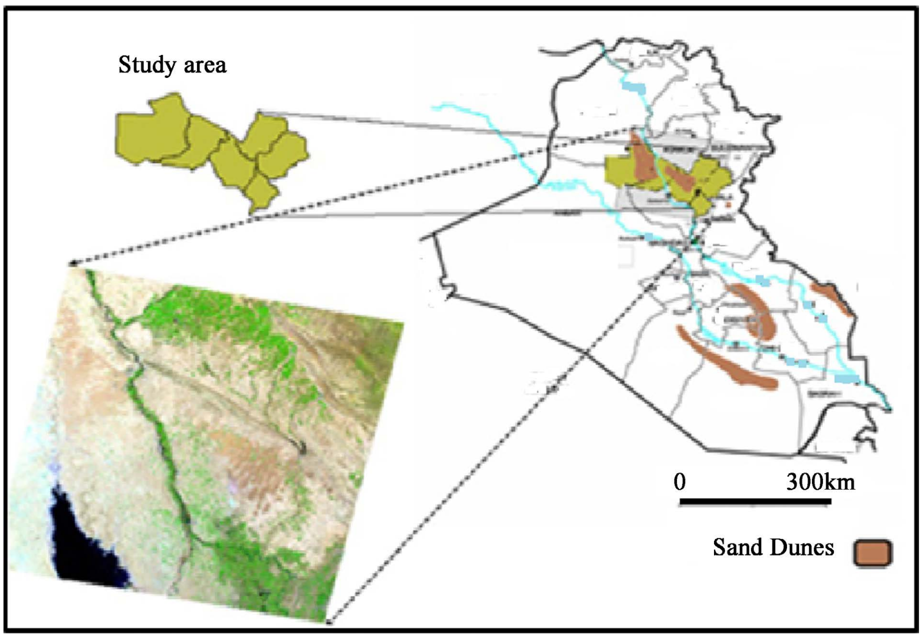

Figure 20. Location map of the study area [65].

other hand, there was a significant increase in the vegetative cover of 289.3% in the Al-Daur district. This increase was result of the use of modern irrigation techniques for agriculture, such as sprinkler irrigation systems for irrigation of growing plants in the mentioned district. The vegetation cover was concentrated near the riverbanks and in the lands which have water wells as a major sources of irrigation. The spatial distributions of the vegetation cover in 1988 and 2009 are shown in (**Figure 21**). The study also indicated a significant increase in areas of sand dune accumulations and in their movement rate toward the surrounding lands in the period from 1988 to 2009. The highest increase in their accumulations was in the Baiji district accounting for 66.4% of the entire area of the Baiji district. The movement of drifting sands and sand dunes destroying crop lands, canals and infrastructure as well as reducing agricultural productivity and caused worsening of living conditions. The Al-Aith site (Al-Daur district) ranked second in the increase of sand dune encroachment in 2009 in comparison with 1988, and was characterized by its high movement rate forming a longitudinal shape in the direction from north-west toward south-east in line with the direction of prevailing winds in the region. The spatial distributions of sand dunes accumulation in this period are shown in (**Figure 22**).

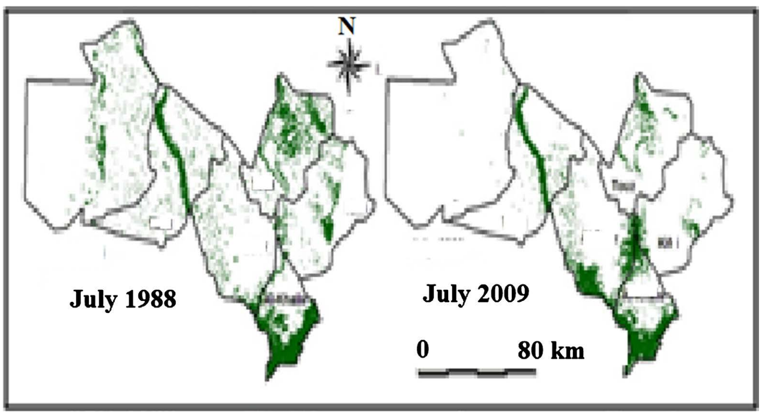

Figure 21. The Spatial Distribution of the Vegetation Cover in the Study Area 1988 and 2009.

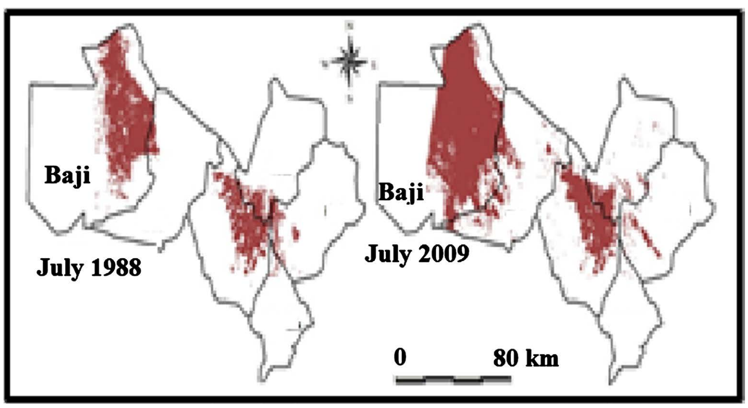

Figure 22. The Spatial Distribution of Sand Dunes Accumulations in the Study Area 1988 and 2009 [65].

As a secondary result, the study indicated decrease in water surface areas in the vicinity of the which were covered by the same satellite imagery, namely the Tharthar Lake and the flood relief Shari Lake, which disappeared completely (**Figure 23**) [65].

An updated study on the desertification of Baiji district, published in 2021, showed much worse situation in this area than it had been in 2009 [66]. The study utilized meteorological data records for 50 years extending from 1970 to 2020 and used statistical approach to derive the standardized precipitation index (SPI) which can be considered as a good measure of drought conditions in any area [67] [68]. The obtained results showed 29 years of drought conditions ranging between extreme to normal droughts, and the remaining yeas were moderately wet except for one year as being very wet. The study also revealed a drop of 55 mm in the average annual precipitation from 216.0 mm in 1970 to 158.0 in 2020 giving an annual drop of precipitation rate of 1.12%. The increase of sand dunes covered area from 1995 to 2019 was then measured using two Landsat TM image taken on 26th April 1995 and on 11th May 2019 respectively and both having high resolution of 30 m. The results indicated that the 1312.29 km^2 of sand dunes covered area that existed in 1995 had increased to 2162.49 km^2 in 2019, which indicates an increase of 30.2%. In the absence of any amelioration communal efforts, the whole Baiji district will transform very soon to desert covered by aeoline dunes similar to the existing once which are shown in (**Figure 24**).

Many large areas in Iraq suffer from the same conditions of severe desertification leading to formation of sand dunes. Increasing areas covered by these dunes are documented for areas such as The-Qar and Al-Muthanna governorate and in Najaf district, [69] [70] [71]. As a matter of fact, sand dunes at the present cover

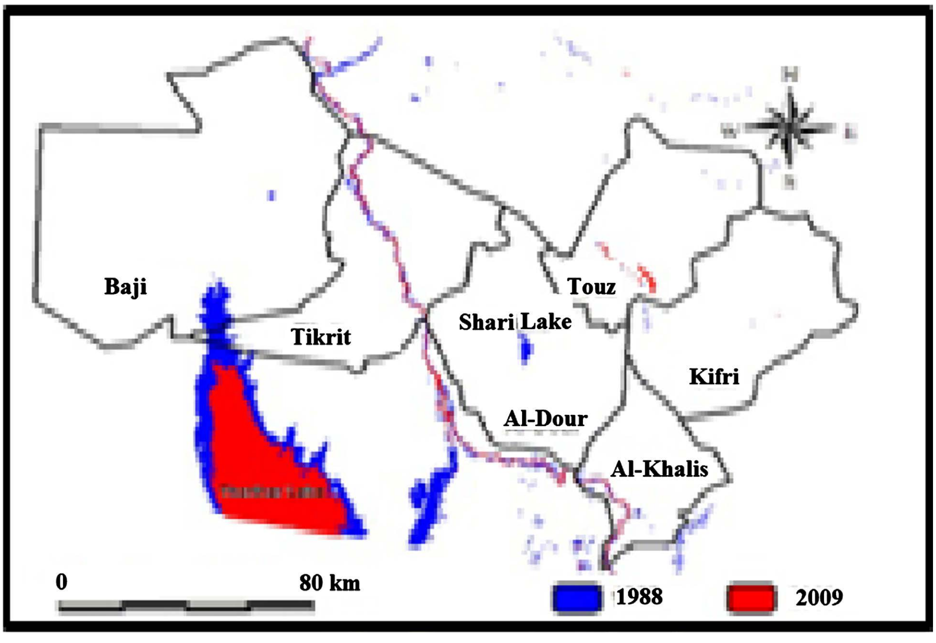

Figure 23. Water bodies Surface Areas in 1988 and 2009 [65].

Figure 24. Photographs of sand dunes covered areas in Baiji district [66].

an area of more than two million donums (500,000 ha) in the middle and south of Iraq in the form of continuous belts, the first; the northern belt, extends from Baiji district to Al Dour district and extends to the area between the Tigris river and the Iraq-Iran borders along Makhool and Hamrin mountain range, the second; the eastern belt, continues from the area of Muqdadia town in Diyala governorate towards Ali-Alghrbi, Al-Teeb and Chlat in Messan governorate, and the third; the middle belt, is located between the Euphrates river to the west and Tigris and Garaf rivers in the east, and extends from the Greater Musayab project to the Euphrates river down toward to Nasiriya and Samawah cities [72]. These belts which affect many towns, cities, industrial and irrigation projects are open for more encroachment on more lands in view of the expected climate change impacts exasperating the desertification conditions, and the absence of any meaningful efforts to combat their formation.

9. Dust and Sand Storms (SDS)

The Eastern Mediterranean region is located within a dusty belt which is surrounded by two of the largest deserts in the world; North African desert and the Arabian desert. The mid-latitude westerlies and local prevailing winds enable the long-range transport of mineral aerosols originating from these two deserts into Iraq and the surrounding countries. Sand and mineral dust are frequently mobilized from sparsely vegetated drylands forming "sandstorms" and "dust storms" in the region. These drylands are reckoned as a major source of dust storms since the 1980s, for which the internationally agreed definition of a dust storm involves a reduction of visibility to less than l000 meters [73]. In the Tigris and Euphrates basin in Iraq and Syria; (Location 11 in **Figure 25**), dust storms of Dust Optical Depth (AOD) greater than 0.2 have a frequency of occurrence of more than 20% over most of the area [74]. The Aerosol Optical Depth (AOD) value is defined as the measure of desert dust distributed within a column of air from the Earth's surface to the top of the atmosphere and it provides a quantitative measure of the extinction of solar radiation due to aerosols scattering and absorption [75]. Heavy dust regions are defined by (AOD) values higher than (0.3), but around deserts its value is between (1.0) and (3.0) [76]. The mean observed (AOD) values during (2003-2016) over, Syria, Iraq, Saudi Arabia, and the lower portion of the Gulf are shown in (**Figure 26**) [76].

Drivers of dust storms in Iraq are mainly climatic changes, but upstream water control is playing an important role in exasperating water scarcity in the country causing more dry land and desertification and intensifying these storms.

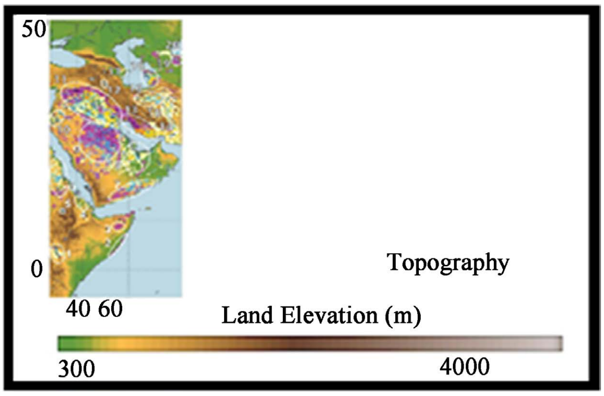

Figure 25. Distribution of the percentage number of days per season (March, April, and May) with Dust Optical Depth > 0.2 over Eastern Africa and the Middle East. The colour shadings are the same as in Figure 3.5. The white circled source areas are numbered as follows: 1, Chalbi Desert of Kenya; 2, coastal desert of Somalia; 3, Nogal Valley of Somalia; 4, Danakil Desert of Ethiopia; 5, Lake Tana of Ethiopia; 6, northeast Sudan; 7, Hadramawt region; 8, Empty Quarter; 9, highlands of Saudi Arabia; 10, Jordan River Basin of Jordan; 11, Mesopotamia; 12, Urumia Lake of Iran; 13, coastal desert of Iran; 14, Hamun-i-Mashkel; 15, Dasht-e Lut Desert of Iran; 16, Dasht-e Kavir Desert of Iran; 17, Qobustan in Azerbaijan; 18, Atrek delta of Turkmenistan; 19, Turan plain of Uzbekistan; and 20, Aral Sea [74].

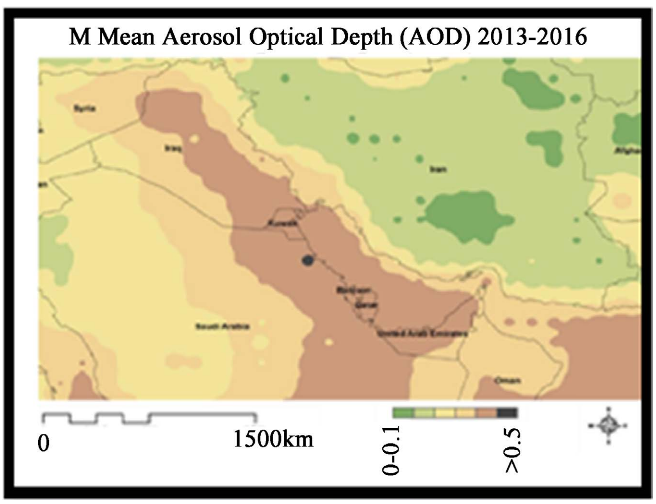

Figure 26. Mean AOD values of the Period 2003-2016 in the Middle East [76].

In the upper part of the basin, in Syria, they are due to anthropogenic sources. In Saudi Arabia and in Jordan there is an extensive area of anthropogenic sources, mixed with hydrological sources. In Yemen large dust sources are associated with river fans at the base of the coastal escarpment in Hadramawt, while Iran has a prominent source along its west coast and the northwestern part which are anthropogenic. Sand and dust storms (SDS) in the Middle East and North Africa (MENA) are determined by numerous climate systems and pathways. Most of dust storm systems can be classified into Summer Shamal and Frontal dust storms. Shamal dust storms usually occur across Iraq, Kuwait, western part of Khuzestan plain, and some parts of Arabian Peninsula, whereas Frontal dust storms occur across Jordan, Israel, and the northern Arabian Peninsula. There are six main (SDS) dust storm paths dominated by the climate in MENA (**Figure 27**).

The first path originates from the Mediterranean Sea passing over Cyprus and enters Syria. The second path is under the control of a high-pressure system over east of Europe. The third path comes from south of the Mediterranean Sea or coastal of northern Africa and always strikes south of Syria or the north border of Jordan and Saudi Arabia. The fourth path is from north of Africa which usually passes across Egypt, north of the Red Sea, and blows toward southeast in Saudi Arabia. The fifth path is also located in the depressions in north of Africa. The last path originates from Sistan Plain at the Iran-Afghanistan border which is controlled by anticyclone over central Asia. Air masses from the Mediterranean Sea are important factors for the generation of sand and dust storms which cover about 70 percent dust storm events [77]. The frequency and intensity of

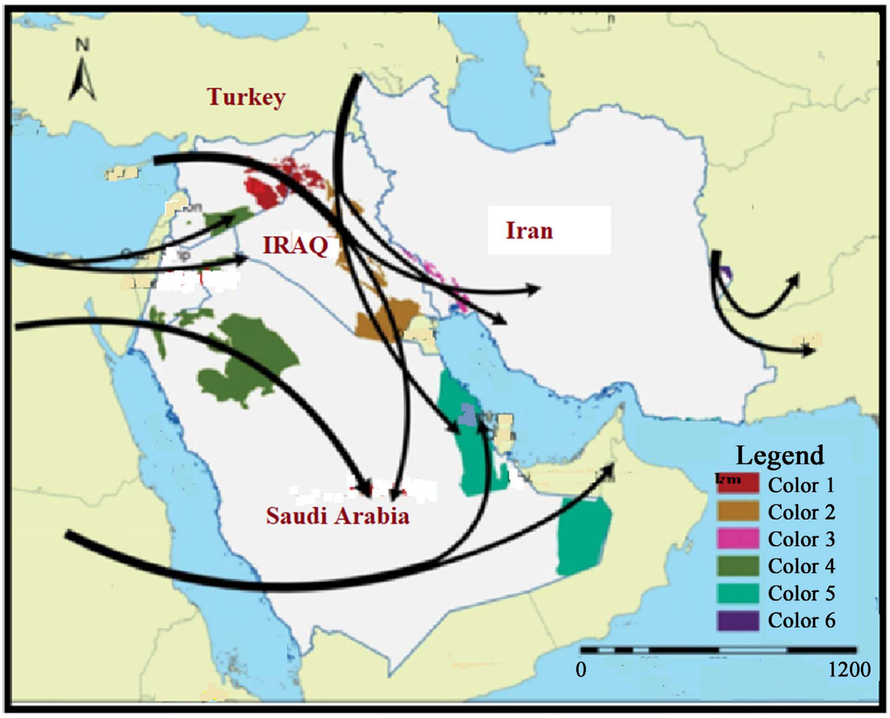

Figure 27. Sand and Dust Storms (SDS) Path and Source Clusters in (MENA) [77].

some extreme climate events in the region, including (SDS), have increased as a consequence of global warming and will continue to increase under medium and high emission scenarios. The anthropogenic (GHG) emissions are also increasing the frequency and intensity of drought and drive for more (SDS) in north-eastern Brazil, the Mediterranean, most of Africa and north-eastern China. These changes will impact ecosystems, food security and land processes including (GHG) fluxes [78].

The occurrence of (SDS) over Iraq has been discussed in length in one important paper published in (2013), and their origins, causes and characteristics were outlined [79]. Another study published in August 2019 outlined the dynamics involved in (SDS) over the country by utilizing the Normalize Difference Dust Index (NDDI) to monitor them using MODIS/Aqua Surface Reflectance Daily Global V006 products for calculating (NDDI) to monitor, map, and assess the development and spread of dust storms over the arid and semi-arid territories of the country. The study covered the period between 29th June to 8 July 2009, which was considered as one of the worst dust storm period of all times in Iraq. The area covered by the storm was largest on July 5 and smallest on June 29 (**Table 1**). Moreover, a positive relationship was found between the dust storm covered area and wind speed, *i.e.*, an increase in wind speed resulted in an increase of the dust storm area. The most significant dust-related activity occurred in the northwestern and western parts of Iraq where large areas are characterized by lack of vegetation during the summer season (June, July, and August) and no rainfall. The dust emissions in the Tigris and Euphrates alluvial plain reached its peak during the month of July as can be seen from (**Figure 28(a)** & **Figure 28(b)**. Shamal winds had mobilized the dust and sand particles from the Tigris and Euphrates River Basin and carried it towards Western Iran and the Persian Gulf [80].

Table 1. Dust Storm Areas for June29 to July 8, 2009 [80].

Date (2009)	Dust Area (Km^2)	Percentage of Dust Storm Area/ Percentage to the Area of the Country
June 29	52,381.3	6
June 30	141,593.4	17
July-1	51,425.7	7
July-2	57,533.8	8
July-3	234,754.1	27
July4	251,102.8	29
July-5	540,640.8	71
July-6	209,680.6	25
July-7	206,160.8	24
July-8	128,364.8	15

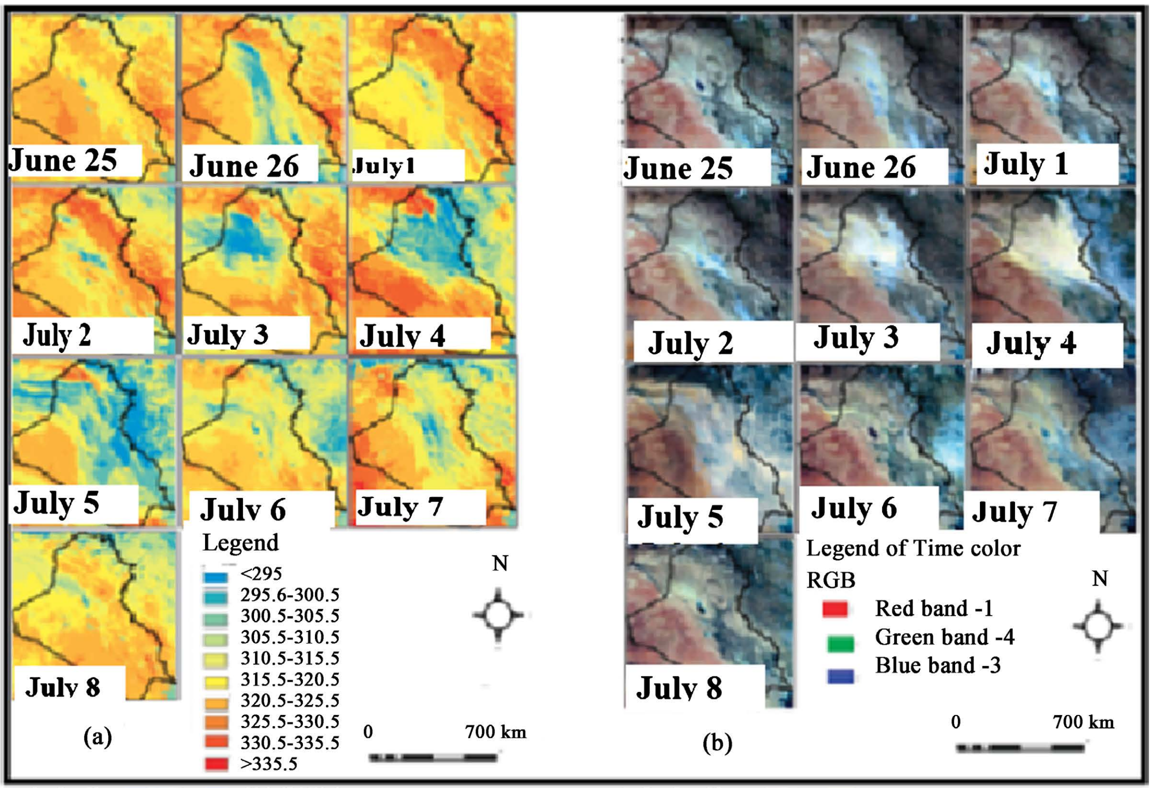

Figure 28. (a) TB images of Aqua MODIS band 31 (10.78 - 11.28 μm) for 10 days (June 29 - July 8, 2009) over Iraq and surroundings; (b) Aqua MODIS true-color images bands (1, 4 and 3) respectively for 10 days (June 29 to July 8, 2009) [80].

Most (SDS) events over Iraq are not local but they are normally part of much larger events taking place over wide area within the Eastern Mediterranean region and the Arabian Peninsula. This has been proven by a study of six frontal storms that had taken place during the cold period (October-March) between 2016 and 2018. The study concentrated on atmospheric circulation patterns and force dynamics that triggered the fronts and the associated pre or post frontal dust storms. In these events it was proven by using satellite imagery and mathematical model that cold troughs of Shamal winds mostly located over Turkey, Syria and north Iraq played a major role in the front propagation at the surface, while cyclonic conditions and strong winds facilitate-ed the dust storms, [81]. In Iraq, (SDS) rank prominently among the most adverse weather events, which have resulted from natural climatic changes and anthropogenic drivers. Their frequency and intensity are expected to rise over the present levels in view of the present deteriorating conditions and the gross negligence of the authorities to take meaningful actions to combat them. This is already showing their impacts, causing much hardship and health hazards.

10. Conclusions

1) Climate change impacts worldwide, have given rise to adverse problematic conditions in the East Mediterranean countries and more specifically in Iraq.

This has been indicated by water scarcity, intense heat waves and higher atmospheric temperatures and frequent recurrence of droughts; all leading to more loss of vegetation cover, desertification and (SDS). The environmental conditions were worsened by the American invasion to Iraq in 2003. While humanitarian pretexts of helping the Iraqi people against the previous regime were used, the constant movement of heavy armors all over the country had led to the destruction of its vegetal ecosystem and caused much deterio ration of the land and forming new (SDS) sources, in addition to using depleted uranium ammunition which had contaminated large part of Iraq hindering the possibilities of reclamation for long time to come, [82]. The negative impacts of climate change gain more weight for the Middle East as some of the countries in the region, such as the Kingdom of Saudi Arabia, Iraq, Syria and Jordan have some of the most religious sites in the world and the recently thriving religious tourism industry will suffer great decline as the present adverse climatic conditions continue in the future [83].

2) Rainfall and temperature records over Iraq indicate decreasing rainfall and increasing temperatures in the future, [84]-[89]. Climate change impacts and declining water resources of the Tigris and Euphrates rivers have undermined Iraq's agricultural sector. The two rivers are shared with Turkey, Iran and Syria who continue to dam them and divert more water at the expense of Iraq's share. Severe droughts have hit both Syria and Iraq who suffered their worst since 1940. Such droughts had happened in 2007 till 2009 and 1998 and 2000 and continue with precipitation levels dropping up to 70 percent below annual averages [90]. Climate change and anthropogenic impacts are increasing the population hardship through loss of revenues, increased health hazards and forced migration due to water scarcity. Since Turkey, Iran, and Syria are affected by the same negative climatic changes, then this means that in the absence of water sharing agreement the heavies damage will fall upon Iraq. In such case utmost efforts must be made by Iraq to conclude fair water sharing treaty with these countries within a comprehensive economical plan to ease this situation. It must be understood that instability of Iraq due to forced immigration of the population and social unrest can spill over to the neighboring countries and may cause conflicts [91] [92] [93] [94] [95].

3) Climate change impacts on Iraq have regional domain which includes all the East Mediterranean countries and the Arabian Peninsula. Any future research and modelling studies must cover the whole region to have meaningful results. This research should be developed to forecast future changes in parameters, such distributions and magnitudes of precipitation, atmospheric temperatures, wind circulation system anomalies, and to better understand aerosols characteristics, in addition to predicting future drought conditions and progressive desertification and (SDS) sources and extents. Mitigations measures will have to be done in cooperation between all the countries of the region and will have to consider initiating and sustaining integrated programs for combating droughts

by using unconventional water resources, afforestation, improving vegetation cover, adopting proper land management procedures and halting the progression of sand dunes. This does not mean to exclude bilateral cooperation if possibilities of such operation exist. An example is the agreement signed by Iraq and Saudi Arabia in February 2022 which includes cooperation in several fields, among them is to combat desertification and preserve forests, pastures and biodiversity [96].

4) In the multilateral efforts to mitigate climate change research work by the Middle East countries, we suggested to establish an Intergovernmental Panel on the same lines of the (IPCC) under the name of the “The Middle East Regional Panel on Climate change (ME-RPCC)”. Iraq may take the initiative of forming this panel which shall include all the countries in the region to coordinate with the IPCC, WMO, and UNEP and other International bodies on climate change research. Tt shall pioneer, encourage, organize scientific research in all member countries, analyze the results and store them into the form of accessible data base, not to mention issuing reports and summaries to policy makers. Scientific research managed by (ME-IPCC) shall be mostly of regional nature directed into issues common to the member states.

5) Alongside strengthening official agencies and legislation dealing with the environment, the governments of the region need to get the private sector involved in the preservation efforts and should also take more initiatives to integrate environmental considerations into their planning. Moreover, governments must move from the charity attitude of asking international organizations for grants to take corrective measures towards the social responsibility concept and the environmental responsibility perception by appropriating the required budgets by the countries themselves. None of this can succeed without active participation of the people to preserve the environment which is encouraged by the media and the NGOs to raise the awareness and willingness to do the necessary works [97].

6) In the amelioration efforts, it is also suggested to set up one fund by the Middle East countries under the name of “The Middle East Regional Fund for Combating Desertification (ME-RFCD)” to plan, finance and support efforts of reducing climate change impacts in combating desertification in projects such as afforestation, reducing and eradication of sand dunes, halting desertification in ways similar to the green dam initiatives in Algeria, and the Great Green Wall initiative for the Sahara and Sahel in Africa, [98] [99].

7) Iraq now is facing an existentialist situation due to climate change impacts on its environment, agriculture, health and economic sectors. This will certainly lead to more poverty, social unrest and migrations. The water crisis in the country is only one side of the problem. In Iraq, the ever-growing shortage of water is threatening the fertile land with desertification [100]. The growing population and declining water together with increasing heat waves intensity and (SDSs) are aggravating the situation beyond human tolerance [101]. The Iraqi Government

has been contented so far by drawing down strategies and programs with support from UN organizations on such matters as reducing and stopping land degradation, combat desertification, and environmental action plans [102] [103] [104], but unfortunately, nothing of all the actions proposed by these strategies and plans have been seriously implemented due to internal political rivalries, security problems and lack of appropriations. No diplomatic efforts have been taken with Turkey and Iran to solve the Tigris and Euphrates water issue, at least to equitably share the damage inflicted by climate change, if not to solve this matter. Moreover, no serious action has been taken to promote cooperation with neighboring countries to have, short, medium or long term plans to reduce negative environmental issues. This immobility and stagnation have caused concern of international organization who have raised their voices asking the government of Iraq for action and at the same time giving their many recommendations [105] [106].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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