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Sustainable Adaptation Plan in Response to Climate Change and Population Growth in the Iraqi Part of Tigris River Basin

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Abstract: Climate change and population growth play crucial roles in the planning of future water resources management strategies. In this paper, a balancing between projected water resources and water demands in the Iraqi Part of the Tigris River Basin (TRB) was evaluated till the year 2080 based on RCPs 2.6, 4.5 and 8.5 and population growth. This paper examined a sustainable adaptation plan of water resources in the TRB considering three scenarios; (S1) as no change in the current strategy, (S2) as improved irrigation efficiency and (S3) as improved irrigation and municipal water use efficiency. The results showed a decline in streamflow will occur in the range from 5 to 18.4% under RCP 2.6 and RCP 8.5, respectively. The minimum increase in water demand is expected for RCP 2.6 (maximum increase for RCP 8.5) by 51.8 (208.2), 9.9 (42) and 1.2 (7)% for the municipal–industrial, irrigation and environmental water demands, respectively, compared with the RP. The main finding indicated that S1 is the worst scenario, with water stress in four provinces, especially on the warmest RCP. Whereas, under S2 and S3 conditions, water stress can be eliminated. Increasing ambition towards adaptation becomes obligatory for developing sustainable water sources, supporting water food securities and increasing resilience towards climate change.

Keywords: SWAT; LARS-WG; CROPWAT-8; WEAP; climate change; adaptation

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1. Introduction

Climate change induced by global warming is evidenced to alter the hydrologic cycle [1–3]. Temperature increase is the main driver of the spatiotemporal variation in precipitation and evapotranspiration patterns [4,5]. In arid and semi-arid regions, the worst case is an increase in evapotranspiration and a decline in precipitation. This results in a reduction in streamflow due to greater water losses from lakes, reservoirs and soil [6,7]. Moreover, drought occurs naturally in the hydrologic system but climate change is accelerating the frequency, intensity and duration of this extreme hydrologic event [8–10].

The Middle East Region (MER) is subjected to greater increases in temperature and changes in precipitation patterns compared with other regions worldwide [11]. Furthermore, hotter and drier weather conditions will dominate the MER during the current century [12,13], and exceptional heatwaves, droughts, dust storms and flash floods will occur [14]. Extreme climate events pose a real threat to water security and food security in the MER [15,16].

Iraq is part of the arid and semi-arid region of the MER, and, in Iraq, about 98% of the agricultural, municipal, environmental and industrial water needs depend on the Euphrates and Tigris Rivers [17]. However, most previous works have reported that the water resources of both rivers will decline due to human activities in upstream countries and climate change effects [17–19]. On the other hand, the water demand is expected to increase due to increased evaporation, a decline in precipitation and rapid population growth [20,21].

Many researchers have argued that improving water resources management plans, increasing water use efficiency and demanding conservation in irrigation and municipal sectors can serve as adaptation strategies to minimize vulnerability and support the resilience of the water resources system [22–24]. Furthermore, these adaptation strategies support sustainable development and improve water security and food security [25–27]. Despite increased water use efficiency providing more water to the stream, there is no evidence of this occurring in the TRB. The balancing of water resources/water demands is subject to two stress factors, climate change and population growth. Therefore, this scientific gap needs more understanding to explore the robust factors that control the water resources/water demands function.

The Soil and Water Assessment Tool (SWAT) is efficiently implemented as a hydrological model for future water resources prediction in various climate regions worldwide [28–30]. The Long Ashton Research Station Weather Generator (LARS-WG) model is applicable in water resources analysis as an efficient tool for the prediction of future climate variables [31,32]. One of the benefits of the water evaluation and planning (WEAP) model connected with the SWAT model is the spatiotemporal balancing of the water resources and water demand to optimize water resources management under current and future climate conditions [33,34].

The main aim of this paper is to evaluate three scenarios for water resources management plans on the Iraqi part of the Tigris River Basin (TRB) considering the impacts of climate change and population growth. The suggested scenarios are the following: Scenario 1 (S1) represents no change in current water use efficiency, Scenario 2 (S2) suggests improving irrigation efficiency to 70% and Scenario (S3) involves improved irrigation efficiency to 70% plus improving municipal water use to 450 liters per capita per day (l.p.c.d) in the provinces that exceed this demand. These adaptation scenarios are designed with consideration of sustainable water sources, supporting water security and food security as well as increasing the resilience of the ecosystem. For this purpose, the future water resources and water demands of the Iraqi part of the TRB were spatiotemporally balanced in the context of stakeholder requirements and available surface water in a spatiotemporal manner based on expected climate and population in a novel method of the water resources evaluation of arid and semi-arid regions. The methodology provides more understanding of the relationship between future water resources and water demands based on changes in climate and population.

2. Materials and Methods

2.1. Study Area

The TRB extends over 221,000 km^2, covering areas of Iraq, Turkey, Iran and Syria of 123,981, 54,145, 41,990 and 884 km^2, respectively (Figure 1). The Batman, Botan and Feesh Khabour headwaters form the Upper Tigris (UT), as well as four effective tributaries which feed the Tigris River; namely, Greater Zab (GZ), Lesser Zab (LZ), Adhaim (AD) and Diyala (DL). These headwaters and tributaries contribute about 99% of the water resources of the Tigris River [34].

The TRB comprises almost 23.4 million inhabitants distributed in Iraq, Turkey, Iran and Syria, respectively. Irrigation in Iraq consumes about 70% of the Tigris River's water resources [35,36] (Table 1 shows the irrigated area). The population of the Iraqi part of the TRB is distributed over the following eleven provinces: Duhok, Ninawa, Salah-addin, Erbil, Sulaymaniyah, Kirkuk, Diyala, Baghdad, Wasit, Maysan, Basrah and part of the Dhi Qar Province. The population of the TRB inside Iraq is presented in Table 1 based on the censuses of 1987 and 1997 and the 2020 estimation provided by the Iraqi Ministry of Planning (MoP). The Hawizeh Marshland and Shatt Al-Arab River are also fed by the Tigris River to maintain 45,200 ha as a submerged area and provide water at 50 m^3/s, respectively.

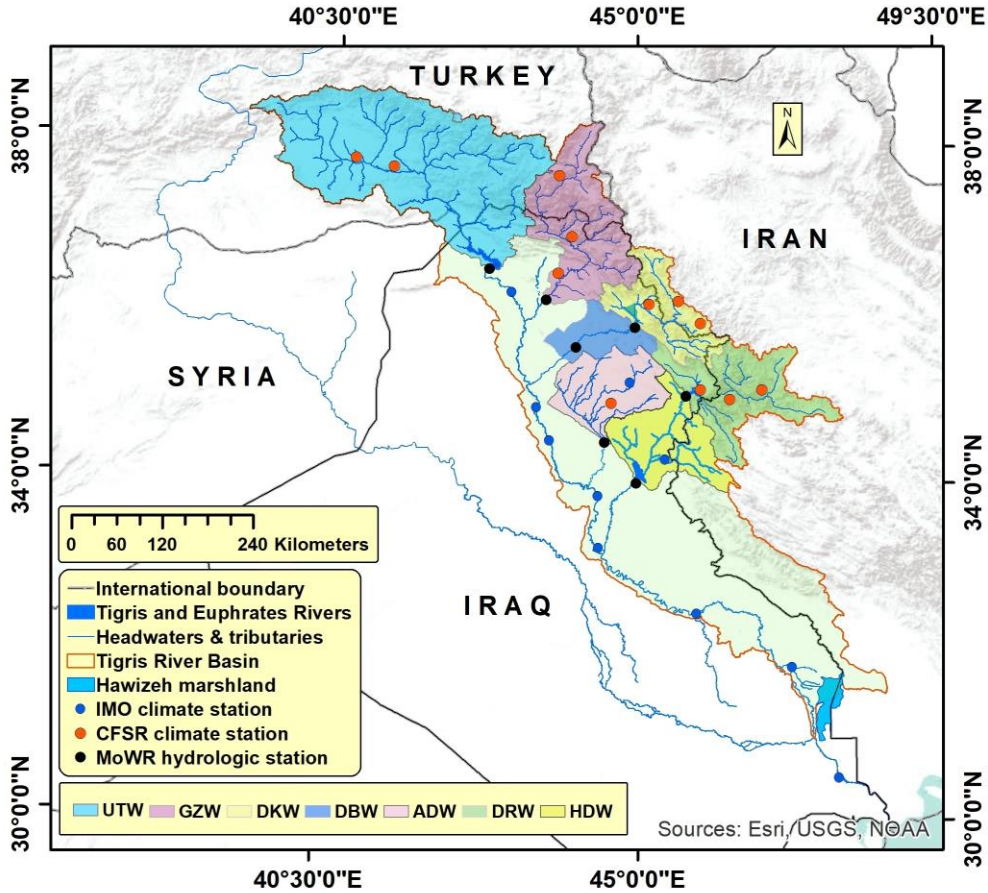

Figure 1. Location map of TRB.

Table 1. Irrigated areas, marshland areas and population on the Iraqi Part of TRB.

Province	River	Irrigated Area (ha)	Marshland Area (ha)	Census 1987 (inh *)	Census 1997 (inh)	Estimation 2020 (inh)
Duhok	Tigris	450	-	207,216	missing	565,853
Ninawa	Tigris	182,925	-	697,191	1,115,141	2,030,181
Ninawa	GZ	10,100	-	-	-	-
Salah-Addin	Tigris	186,450	-	551,031	662,117	1,423,915
Erbil	GZ	28,675	-	165,491	missing	652,394
Sulaymaniyah	Diyala	20,625	-	238,614	missing	573,565
	LZ	4850	-	103,596	missing	410,560
	Adhaim	-	-	missing	missing	62,528
Kirkuk	Adhaim	-	-	418,696	459,529	999,869
	LZ	145,175	-	29,828	32,178	99,322
Diyala	Diyala	239,150	-	371,032	457,890	805,155
Baghdad	Tigris	52,625	-	3,454,494	5,008,262	7,055,854
Wasit	Tigris	569,475	-	493,101	668,599	1,378,129
Maysan	Tigris	159,650	45,200	487,448	631,712	1,142,131
Basrah	Tigris	32,900	-	524,929	1,218,783	2,308,286
Dhi Qar	Tigris	52,400	-	290,724	396,304	716,158

* Indicated to inhabitant.

The Mediterranean and the subtropical-continental climate zones predominate in the northern and southern parts of the TRB, respectively [37,38]. Most of the precipitation occurs between November and April in the north and east of the basin, specifically in the Turkish highlands and Zagros Mountains, and ranges between 600–800 mm/y. Snowfall normally occurs during January-March at high altitudes in these regions [39,40]. However, the precipitation in the southern part of the basin falls in rainfall form at a rate of less than

100 mm/y [20]. The climate in the northern part of the TRB is relatively hot and dry during the summer and rainy–cold during the winter with the minimum temperature reaching −9 °C [41]. The average contribution of the headwaters and tributaries to the streamflow of the Tigris River are 21, 12.7, 7.8, 0.79 and 4.6 Billion Cubic Meters/year (BCM/y) for the UT, GZ, LZ, AD and DL, respectively [39].

2.2. Climate, Streamflow, Population and Water Demand Modeling

LARS-WG is a downscale stochastic weather generator model developed to generate current and future climate variables, including solar radiation, precipitation and minimum and maximum temperatures, at a single site based on outputs of regional and global climate models [42]. LARS-WG implements a Semi-empirical Distribution (*SD*) to predict the precipitation, solar radiation and length of dry and wet seasons. The *SD* histogram (equation 1) is divided into ten intervals in the range of $x_{i-1},\ x_i$.

$$SD = (x_0,\ x_i;\ e_i,\ i = 1, \ldots\ldots\ldots, 10) \quad (1)$$

where, $x_{i-1} < x_i$ and e_i is number of events in i intervals extracted from observations.

The minimum and maximum temperatures are stochastically processed based on daily averages and standard deviations considering dry and wet days.

SWAT is a semi-distributed physically-based hydrologic model developed by the United States Department of Agricultural-Agricultural Research (USDA-ARS) and Texas A&M AgriLife Research, Texas University. The model is designed to simulate the quantity and quality of surface and groundwater in large and complex basins for long-term periods under different land management and climate conditions [43].

The SWAT model involves dividing the watershed into sub-basins based on topographic data. The watershed is further divided into Hydrologic Response Units (HRUs) of unique soil, land cover/use and slope. The rainfall–runoff is determined for each HRU within the watershed based on the water balance equation [43].

CROPWAT 8 is a piece of software developed by the Food and Agriculture Organization (FAO) to calculate crop water requirements based on crop, climate and soil data [44]. The software calculates the referenced evapotranspiration (ETo) based on the Penman–Monteith method. More details on CROPWAT-8 can be seen in [44].

The WEAP model was developed by Stockholm Environment Institute, U.S. to process allocation issues in limited water resources regions for sustainable water use. The model utilizes the equal footing equation; the demand side of the equation represents the types of water use, the efficiency of a water system, water reuse, water allocation and water price; the other side of the equation is the supply side, and includes streamflow, lakes and reservoirs, transformed water and groundwater. The WEAP model implements a mass balance equation for all nodes and links of the water resources system in monthly time steps. The model utilizes linear programming to maximize water access by demand from available water instream simultaneously for all nodes and links as integrated maximized coverage of water resources system subjected to mass balance, demand weight and supply preference as constraints of linear programming [45].

2.3. Input Data

The daily precipitation data for 10 climate stations were provided by the Iraqi Metrological Organization (IMO) (Figure 1). The daily precipitation (for 12 climate stations), minimum and maximum temperatures, wind speed, solar and relative humidity (for 22 climate stations including IMO stations) were downloaded from Climate Forecasting System Reanalysis (CFSR) (http://globalweather.tamu.edu/) on 19 May 2021–22 July 2021 [46,47], the climate data cover the period from 1/1/1990 to 31/12/2019. The daily streamflow data (from 1 January 1990 to 31 December 2019) of seven watersheds were provided by the Ministry of Water Resources, Iraq (MoWR). The spatial data used for the SWAT model, including SRTM digital elevation models and MODIS land cover/land use data, were downloaded from USGS Earth Explorer (in April 2021). The FAO soil data were downloaded from http://www.fao.org in April 2021. The agricultural, population and environmental data were provided by the agricultural report [35], MoP and MoWR, respectively.

2.4. Methodology

Using the LARS-WG model, the future precipitation and minimum and maximum temperatures at 22 climate stations were projected for the periods 2021–2040 (P1), 2041–2060 (P2) and 2061–2080 (P3) under the RCPs 2.6, 4.5 and 8.5 of the CMIP-5 with five GCMs (to minimize the uncertainty), namely, BCC-CSM1, CanESM2, CSIRO-MK36, HadGEM2-ES, and NorESM1 based on daily observations recorded from 1 January 1990 to 31 December 2019 as a RP. Furthermore, the observed streamflow during the same RP of the seven effective watersheds, namely, the Upper Tigris Watershed (UTW), Greater Zab Watershed (GZW), Dukan Dam Watershed (DKW), Dibis Barrage Watershed (DBW), Adhiam Dam Watershed (ADW), Darbandikhan Dam Watershed (DRW) and Hemrin Dam watershed (HDW), was projected using the SWAT model based on the projected climate data extracted from the LARS-WG model with the same considered RCPs, GCMs and future periods. The model was calibrated and validated by using the daily observed streamflow in these seven locations as the RP. By using CROPWAT-8 and the recorded and projected climate data, the irrigation water demand was determined for 19 crops (winter wheat, barley, spring maize, autumn maize, sunflower, sorghum, cotton, spring potato, autumn potato, tomato, alfalfa, spring small vegetables, autumn small vegetables, small grains, millet, soybean, date palms, cabbage crucifers and citrus), conventionally planted in 12 provinces distributed over the Iraqi part of the TRB, calculated for the same RCPs, GCMs and considered periods. In the same context, the environmental water demand of the Hawizeh Marshland was calculated and projected for the same considered RCPs, GCMs and future periods. The municipal demand was calculated and projected for the same considered periods based on the population growth (Table 1) and water consumption for each district located at a specific water source. The industrial water demand was assumed to represent 30% of the municipal water demand. Finally, the water resources and water demand were spatiotemporally linked by the WEAP model to maximize water access for each demand based on the suggested scenarios (S1, S2 and S3).

3. Results

3.1. Future Streamflow

During the RP, the observed mean annual streamflow of UTW was 643.2 m^3/s. Under RCP 2.6 (4.5), the streamflow tends to decline by 642.6, 642 and 639.4 (609.0, 594 and 582) m^3/s for P1, P2 and P3, respectively. A greater decrease in mean annual streamflow is expected under RCP 8.5 with 602.6, 580.9 and 578.3 m^3/s for P1, P2 and P3, respectively (Figure 2a). Figure 2b shows that the mean annual streamflow of GZW will decrease from 395.5 m^3/s during the RP to 385.5, 377.7 and 376.3 m^3/s under RCP 2.6 for P1, P2 and P3, respectively. Based on RCP 4.5 (RCP 8.5), the mean annual streamflow is expected to drop to 353.2, 347.4 and 343.4 (344.2, 337.5 and 327.8) m^3/s for P1, P2 and P3, respectively. The future trend of the mean annual streamflow of DKW, shown in Figure 2c, was found to be 119.9, 115.4 and 115.2 m^3/s under RCP 2.6 for P1, P2 and P3, respectively, compared with 122.6 m^3/s during the RP. Whereas, under RCP 4.5 (RCP 8.5), a remarkable reduction in the mean annual streamflow with 110.7, 103.6 and 102.6 (103.4, 100.2 and 96.1) m^3/s for P1, P2 and P3, respectively. For the DBW (Figure 2d), the mean annual streamflow during the RP was 19.8 m^3/s, which will decrease for RCP 2.6 to 15.4, 15.2 and 14.4 m^3/s during P1, P2 and P3, respectively. A greater decrease was found under RCP 4.5 (RCP 8.5) with 13.5, 13.0 and 12.3 (12.0, 11.4 and 10.2) m^3/s for the three periods. The results in Figure 2e illustrated a reduced mean annual streamflow for ADW under RCP 2.6 (RCP 4.5) with 28.58, 28 and 27.86 m^3/s (27.5, 26.6 and 25.5) for P1, P2 and P3, respectively, compared with 28.9 m^3/s in the RP. In the warmest pathway, RCP 8.5, the mean annual streamflow was negatively impacted by climate change, with the decline reaching 24.8, 24.3 and 23.6 m^3/s for P1, P2 and P3, respectively. For DRW, the observed mean annual streamflow was 160 m^3/s in the

RP. However, this magnitude will decline to 90.7, 83.7 and 82.1 m^3/s under RCP 2.6 for P1, P2 and P3, respectively (Figure 2f). The projection under RCP 4.5 (RCP 8.5) showed a greater drop in mean annual streamflow, with 82.8, 70 and 69.7 (77.8, 67.9 and 56.6) m^3/s, at the end of P1, P2 and P3, respectively. Figure 2g shows that the mean annual streamflow for HDW tends to reduce by 17.6, 17.25 and 17 m^3/s under RCP 2.6 for P1, P2 and P3, respectively, while the observed mean annual streamflow was 44.7 m^3/s in the RP. In the same context, a greater reduction will occur during P1, P2 and P3 under RCP 4.5 (RCP 8.5) with 14.34, 12.95 and 12.49 (12.73, 10.8 and 10.5) m^3/s, respectively.

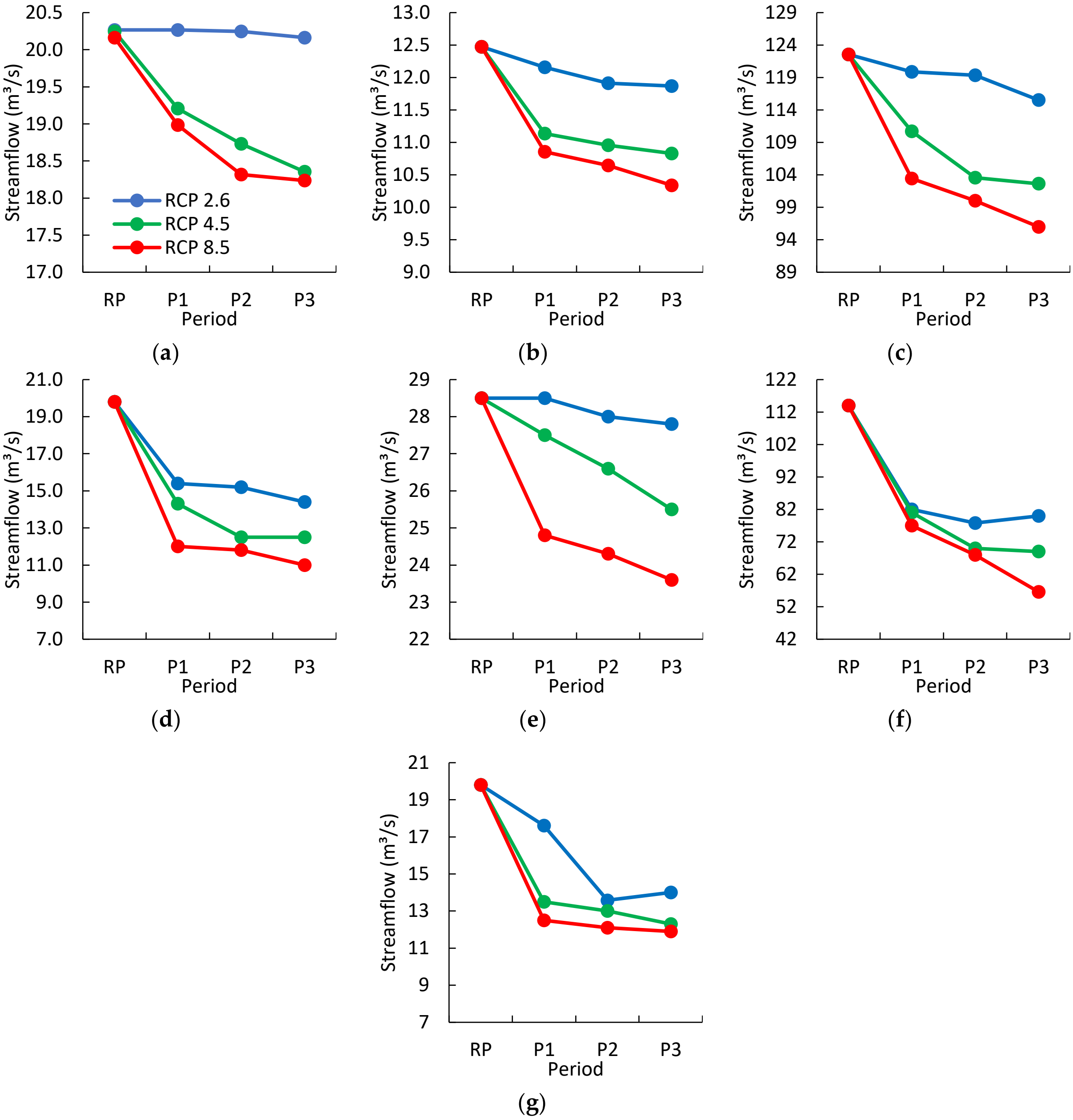

Figure 2. Future streamflow of TRB: (**a**) UTW; (**b**) GZW; (**c**) DKW; (**d**) DBW; (**e**) ADW; (**f**) DRW; and (**g**) HDW.

3.2. Irrigation and Environmental Demand

The results computed by CROPWAT-8 showed an increase in the projected irrigation demand in response to climate change (Figure 3a–n). In the RP, the annual irrigation water released from the Tigris River for irrigation requirements was 28.70 BCM. This magnitude tends to increase to 31.54, 34.33 and 39.63 BCM under RCP 2.6 for P1, P2 and

P3, respectively. However, under RCP 4.5 (RCP 8.5) the annual irrigation water demand is expected to increase to reach 31.73, 34.58 and 40.32 (31.81, 34.97 and 40.76) BCM for P1, P2 and P3, respectively.

In the same context, under RCP 2.6, the annual environmental demand for the Hawizeh Marshland will increase due to climate change with values of 2.01, 2.03 and 2.04 BCM for P1, P2 and P3, respectively, compared with 1.99 BCM in the RP (Figure 3o). A greater increase is expected under RCP 4.5 (RCP 8.5) with values of 2.02, 2.05 and 2.07 (2.02, 2.07 and 2.13) BCM for P1, P2 and P3, respectively.

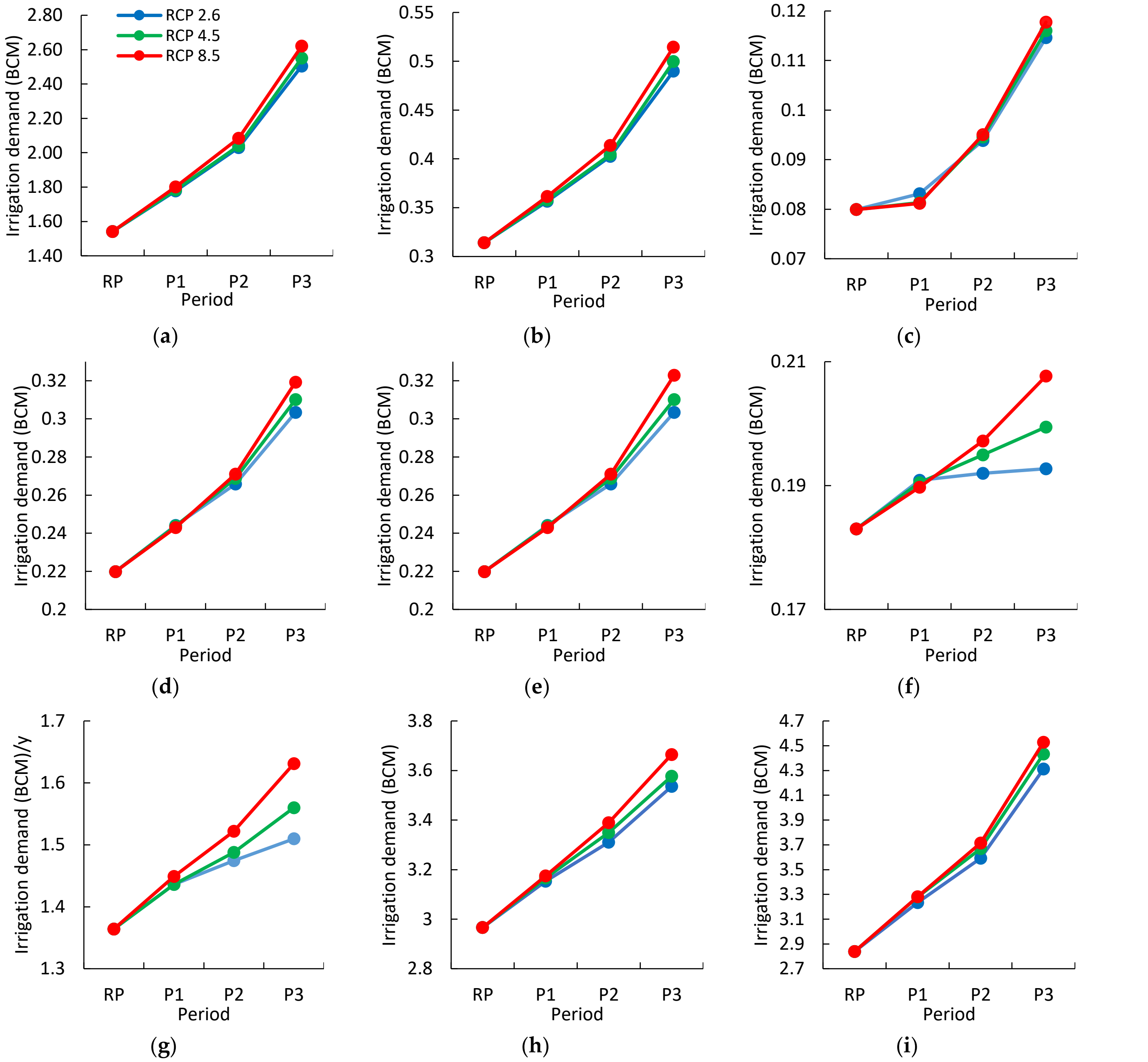

Figure 3. *Cont.*

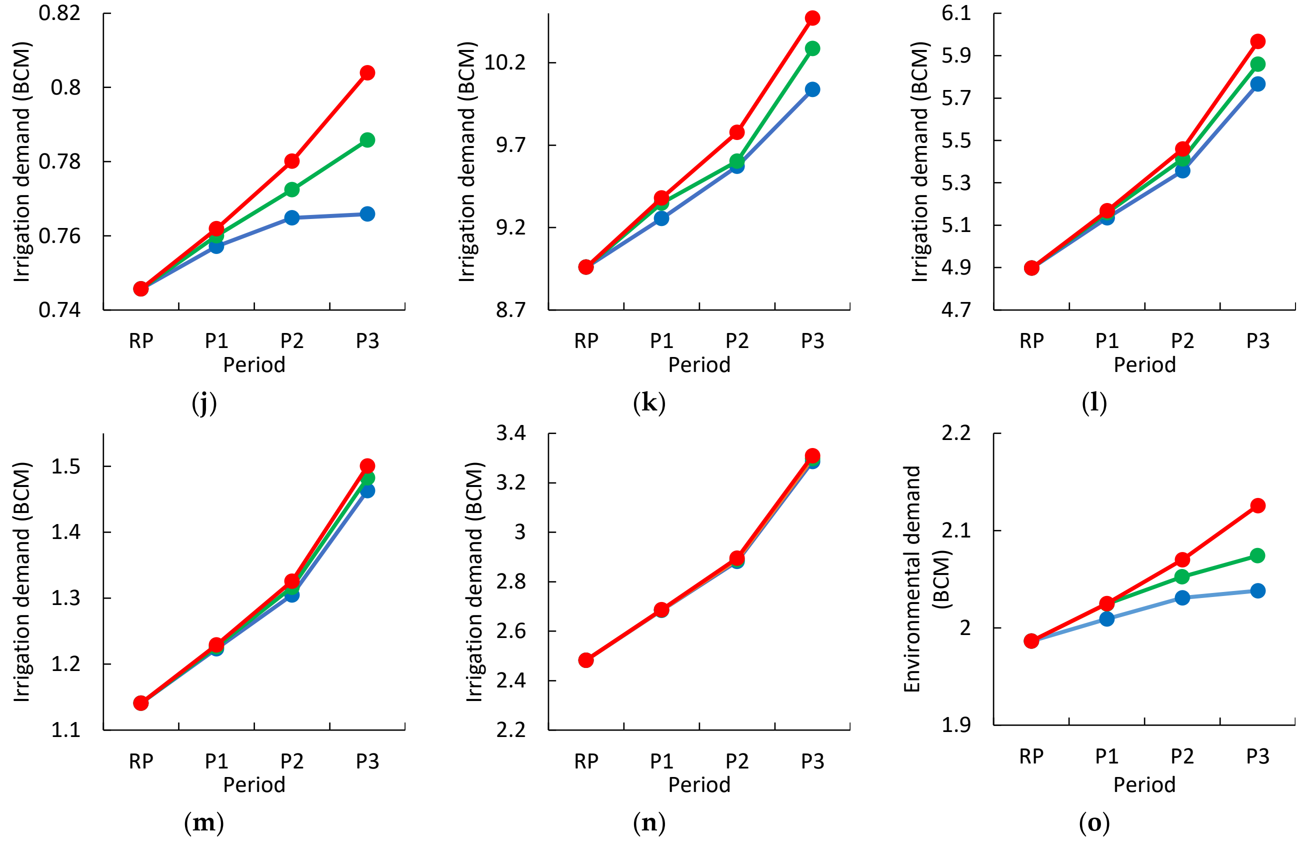

Figure 3. Future irrigation and environmental demand in Iraqi part of TRB: (**a**) Ninawa and Duhok, Tigris [1]; (**b**) Ninawa and Erbil, GZ; (**c**) Sulaymaniyah, LZ; (**d**) Sulaymaniyah, AD; (**e**) Sulaymaniyah, DL; (**f**) Salah-addin, Tigris; (**g**) Kirkuk, LZ; (**h**) Diyala, DL; (**i**) Salah-addin, Tigris; (**j**) Baghdad, Tigris; (**k**) Wasit, Tigris; (**l**) Maysan, Tigris; (**m**) Dhi Qar, Tigris; (**n**) Basrah, Tigris; and (**o**) Hawizeh Marshland. [1] Indicated to province and water source.

3.3. Municipal–Industrial Water Demand

The population is projected to significantly increase due to the high rate of population growth of 2.5–2.7% (Figure 4), almost the same rate of population growth reported by MoP. The population inside the Iraqi part of the TRB tended to rise from 20.2 during the RP to 30.6, 41.1 and 62.3 million inhabitants during P1, P2 and P3, respectively.

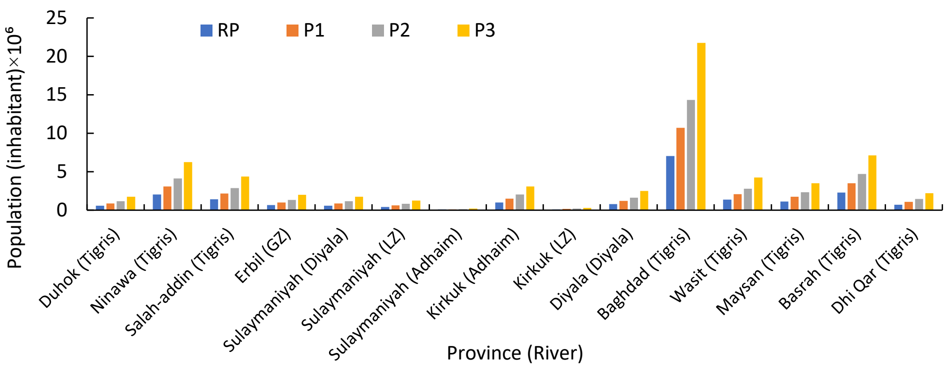

Figure 4. Population growth in the Iraqi part of TRB distribution on water source.

The increase in population is extremely reflected in the positive trend of municipal–industrial demand. The results shown in Table 2 indicate significant increases in the annual municipal–industrial demand in the Iraqi part of the TRB of 8.15, 10.92 and 16.55 BCM in P1, P2 and P3, respectively, compared with 5.37 BCM in the RP. The results show that the capital, Baghdad, will consume 3.20, 4.29 and 6.51 BCM annually during P1, P2 and P3, respectively. Moreover, Salah-addin followed by Ninawa will take the second and third rank of highest annual municipal–industrial demand, with 1.02, 1.37 and 2.08 BCM and 0.58, 0.78 and 1.18 BCM during P1, P2 and P3, respectively. In spite of the fact that Basrah has more residents than Salah-addin and Ninawa, the municipal–industrial demand for Basrah will be less than these provinces, with annual demands of 0.75, 1.01 and 1.53 during P1, P2 and P3, respectively; this is because greater water availability in the stream encourages the residents to consume more water in Salah-addin and Ninawa.

Table 2. Annual municipal–industrial water demand in Iraqi part of TRB.

Province	River	Consumption (l.p.c.d)	Annual Municipal–Industrial Water Demand (BCM/y)			
			RP	P1	P2	P3
Duhok	Tigris	239	0.06	0.10	0.13	0.20
Ninawa	Tigris	296	0.38	0.58	0.78	1.18
Salah-addin	Tigris	1000	0.68	1.02	1.37	2.08
Erbil	GZ	261	0.08	0.12	0.16	0.25
Sulaymaniyah	Diyala	132	0.04	0.05	0.07	0.11
	LZ	132	0.03	0.04	0.05	0.08
	Adhaim	132	0.00	0.01	0.01	0.01
Kirkuk	Adhaim	608	0.29	0.44	0.59	0.89
	LZ	608	0.03	0.04	0.06	0.09
Diyala	Diyala	670	0.26	0.39	0.52	0.79
Baghdad	Tigris	631	2.11	3.20	4.29	6.51
Wasit	Tigris	633	0.41	0.63	0.84	1.28
Maysan	Tigris	672	0.36	0.55	0.74	1.12
Basrah	Tigris	452	0.50	0.75	1.01	1.53
Dhi Qar	Tigris	432	0.15	0.22	0.23	0.35
	Sum.		5.37	8.15	10.92	16.55

3.4. Adaptation Scenarios

3.4.1. Scenario 1 (S1)

Table 3 shows that water stress is expected to occur under the S1 conditions in Diyala for all periods and RCPs, with the range of annual difference between water sources and water demand from 0.3 to 1.9 BCM under RCP 2.6 and RCP 8.5 for P1 and P3, respectively. Basrah will face water stress under S1 conditions under RCP 2.6 (RCP 4.5) and P3, with an annual deficit of water supply of 1.4 (4.5) BCM. Moreover, water stress is also expected in Basrah under RCP 8.5, with a negative supply of 0.7 and 5.7 BCM for P2 and P3, respectively. However, water stress will dominate for P3 in Maysan and Dhi Qar under RCP 4.5 (RCP 8.5), with an annual deficit of 1.2 and 0.3 (2.4 and 0.6) BCM, respectively. All other provinces will obtain sufficient water to meet all requirements, with a maximum annual water surplus in Salah-addin ranging from 28.9 to 22.1 BCM under RCP 2.6 and RCP 8.5 for P1 and P3, respectively.

It is worth noticing that the water resources during the RP are divided into three sectors, 70.6, 17.3 and 12.1% for irrigation, municipal–industrial demand and environment, respectively (Figure 5). Considering RCP 2.6 and S1 conditions, the percentage of municipal–industrial demand will rise due to population growth by 23.6, 28.9 and 37.9% for P1, P2 and P3, respectively. This increase is at the expense of the other sectors because the irrigation (environmental) sector quota will decrease to reach 65.3, 60.8 and 53.1 (11.1, 10.3 and 9.0)% for P1, P2 and P3, respectively. Concurrently with RCP 4.5 (RCP 8.5), the percentage of municipal–industrial demand will also increase by 23.4, 28.7 and 37.3 (23.4, 28.4 and 36.4)% for P1, P2 and P3, respectively. While, under RCP 4.5, the percentage of irrigation (environmental) demand will reduce to 65.5, 61.0 and 53.8 (11.1, 10.3 and 8.9)%, respectively. In the same context, under RCP 8.5, these percentages will become 65.6, 61.4 and 54.7 (11.1, 10.2 and 8.9)%, respectively.

Table 3. Available water in stream considering S1 (BCM/y).

Province	River	RP	RCP 2.6			RCP 4.5			RCP 8.5		
			P1	P2	P3	P1	P2	P3	P1	P2	P3
Duhok + Ninawa	Tigris	+18.5 [1]	+18.2	+17.9	+17.4	+17.1	+16.4	+15.6	+16.9	+16.0	+15.4
Ninawa + Erbil	GZ	+12.0	+11.6	+11.3	+11.2	+10.6	+10.4	+10.2	+10.4	+10.1	+9.7
Salah-addin	Tigris	+30.0	+28.9	+27.9	+26.4	+26.6	+25.1	+23.1	+26.0	+24.1	+22.1
Sulaymaniyah	Diyala	+3.3	+2.3	+2.2	+2.2	+2.3	+1.9	+1.9	+2.2	+1.8	+1.3
Sulaymaniyah	LZ	+3.7	+3.6	+3.5	+3.4	+3.4	+3.1	+3.1	+3.1	+3.0	+2.9
Kirkuk	LZ	+2.4	+2.2	+2.0	+1.9	+1.9	+1.6	+1.5	+1.7	+1.5	+1.2
Diyala	Diyala	+1.3	−0.3	−0.7	−1.0	−0.4	−1.1	−1.4	−0.6	−1.2	−1.9
Baghdad	Tigris	+27.8	+25.6	+23.3	+19.5	+23.0	+20.4	+16.1	+22.3	+19.3	+15.0
Wasit	Tigris	+18.9	+16.3	+13.8	+9.5	+13.7	+10.8	+5.8	+12.9	+9.6	+4.5
Maysan	Tigris	+10.2	+7.9	+5.6	+1.8	+5.8	+3.2	−1.2	+5.2	+2.2	−2.4
Basrah	Tigris	+7.7	+5.2	+2.8	−1.4	+3.1	+0.3	−4.5	+2.5	−0.7	−5.7
Dhi Qar	Tigris	+2.6	+2.0	+1.4	+0.4	+1.5	+0.8	−0.3	+1.4	+0.6	−0.6

[1] Indicated to BCM/y.

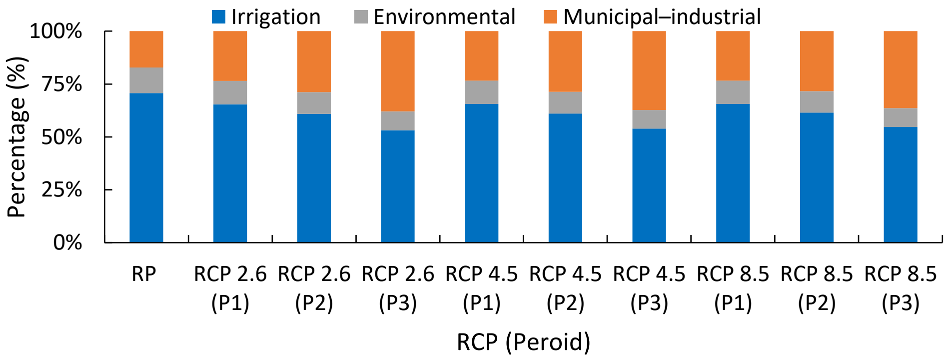

Figure 5. Percentage of water resources distribution among demand sectors considering S1.

3.4.2. Scenario 2 (S2)

For S2, the results shown in Table 4 indicate some enhancement in the available water in the stream compared to S1. Water stress is excluded in Maysan in this scenario. Whereas the water stress in Diyala decreased by a small margin with a minimum and maximum annual range of water source deficits from 0.3 to 1.8 BCM. This is because of the upstream irrigated areas located inside Iran which are not included in this processing. Moreover, the adaptation processes in the small irrigated area located in Sulaymaniyah did not provide a reasonable amount of water in the stream. In Dhi Qar, water stress was successfully eliminated, except under RCP 8.5 and P3 where the water demand was greater than the water source supply by 0.2 BCM annually. For Basrah, water stress can be observed during P3, RCP 4.5 and RCP 8.5, with an annual deficit of 3 and 4.1 BCM, respectively. On the other hand, under S2 conditions, all of the other provinces will receive sufficient water under all RCPs and projection periods. Salah-addin will receive the maximum surplus water in the range of 21.8 to 28.8 BCM annually.

Considering S2, Figure 6 shows that the percentage of municipal–industrial demand will expand for RCP 2.6 compared with the RP, due to an increased population, to 25.2, 29.6 and 38.8% during P1, P2 and P3, respectively. This expansion will reduce the irrigation (environmental) demand by 63.0, 59.9 and 52.1 (11.8, 10.5 and 9.1)%. Similarly, under RCP 4.5, the municipal–industrial demand will also increase compared with the RP by 24.2, 29.4 and 38.1% as a response to population growth during P1, P2 and P3, respectively. Under these conditions (RCP 4.5 and population growth), the irrigation (environmental) demand will decline by 64.4, 60.2 and 52.8 (11.4, 10.5 and 9.1)% for P1, P2 and P3, respectively, compared with the RP. The warmest climate condition (RCP 8.5) will cause more pressure on water resources which, in addition to population growth, will result in an increase in municipal–industrial demand by 23.9, 29.1 and 37.3% for P1, P2 and P3, respectively. Under RCP 8.5, the irrigation (environmental) demand will represent 64.8, 60.5 and 53.5 (11.3, 10.4 and 9.1)% of total water demands during P1, P2 and P3, respectively.

Table 4. Available water in stream considering S2.

Province	River	RP	RCP 2.6			RCP 4.5			RCP 8.5		
			P1	P2	P3	P1	P2	P3	P1	P2	P3
Duhok + Ninawa	Tigris	+18.5	+18.2	+18.0	+17.4	+17.1	+16.5	+15.7	+17.1	+16.1	+15.5
Ninawa + Erbil	GZ	+12.0	+11.6	+11.4	+11.2	+10.7	+10.4	+10.2	+10.4	+10.1	+9.7
Salah-addin	Tigris	+30.0	+28.8	+27.7	+26.1	+26.3	+24.8	+22.8	+25.7	+23.8	+21.8
Sulaymaniyah	Diyala	+3.3	+2.3	+2.2	+2.2	+2.3	+1.9	+1.9	+2.2	+1.8	+1.3
Sulaymaniyah	LZ	+3.7	+3.6	+3.5	+3.4	+3.4	+3.1	+3.1	+3.1	+3.0	+2.9
Kirkuk	LZ	+2.4	+2.3	+2.2	+2.0	+2.1	+1.8	+1.7	+1.8	+1.6	+1.4
Diyala	Diyala	+1.3	−0.3	−0.7	−0.9	−0.4	−1.0	−1.4	−0.6	−1.1	−1.8
Baghdad	Tigris	+27.8	+27.8	+25.9	+23.9	+20.1	+23.7	+20.7	+16.4	+22.6	+19.7
Wasit	Tigris	+18.9	+17.7	+14.4	+10.1	+14.4	+11.2	+6.2	+13.3	+10.0	+4.9
Maysan	Tigris	+10.2	+11.3	+10.0	+7.1	+3.4	+7.4	+4.6	+0.3	+6.6	+3.6
Basrah	Tigris	+7.7	+7.3	+4.3	+0.1	+4.7	+1.8	−3.0	+3.9	+0.8	−4.1
Dhi Qar	Tigris	+2.6	+2.8	+1.8	+0.8	+1.9	+1.2	+0.1	+1.7	+1.0	−0.2

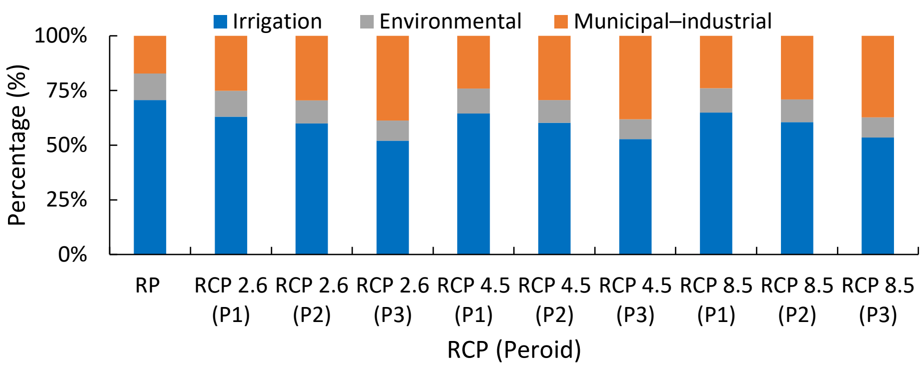

Figure 6. Percentage of water resources distribution among demand sectors considering S2.

3.4.3. Scenario 3 (S3)

S2 reduces the water stress to some extent, but it remains insufficient. Table 5 shows that water stress will be eliminated in all provinces, except in Diyala which will have a water source deficit in the range of 0.01 (under RCP 2.6 and P1) to 1.7 (under RCP 8.5 and P3) BCM annually. Basrah will also face water stress under RCP 8.5 and P3, with an annual lack of 0.2 BCM.

If S3 is applied with the expected population growth and RCP 2.6 conditions, the percentage of municipal–industrial demand will significantly increase by 19.3, 23.3 and 31.5% during P1, P2 and P3, respectively (Figure 7). Whereas, the irrigation (environmental) water demand will shrink compared with the RP due to an expansion in municipal–industrial demand of 69.0, 66.1 and 59.0 (11.7, 10.6 and 9.5)% for P1, P2 and P3, respectively. Moreover, under S3 and RCP 4.5 conditions, the municipal–industrial demand tends to increase by 18.7, 22.9 and 30.7% for P1, P2 and P3, respectively. Compared with the RP, this increase negatively reflected irrigation (environment) demand, with increases of 70.0, 66.6 and 60.0 (11.4, 10.5 and 9.3)% for P1, P2 and P3, respectively. In the same context, under

RCP 8.5, the municipal–industrial demand will rise to 18.2, 22.7 and 30.2% for P1, P2 and P3, respectively. Whereas, the percentage of irrigation (environmental) demand tends to become 70.7, 66.9 and 60.5 (11.1, 10.4 and 9.3)% for P1, P2 and P3, respectively.

Table 5. Available water in stream considering S3.

Province	River	RP	RCP 2.6			RCP 4.5			RCP 8.5		
			P1	P2	P3	P1	P2	P3	P1	P2	P3
Duhok + Ninawa	Tigris	+18.5	+18.2	+18.0	+17.4	+17.1	+16.5	+15.7	+17.1	+16.1	+15.5
Ninawa + Erbil	GZ	+12.0	+11.6	+11.4	+11.2	+10.7	+10.4	+10.2	+10.4	+10.1	+9.7
Salah-addin	Tigris	+30.0	+29.7	+28.9	+27.8	+27.5	+25.9	+24.3	+26.6	+24.9	+23.2
Sulaymaniyah	Diyala	+3.3	+2.3	+2.2	+2.2	+2.3	+1.9	+1.9	+2.2	+1.8	+1.3
Sulaymaniyah	LZ	+3.7	+3.6	+3.5	+3.4	+3.4	+3.1	+3.1	+3.1	+3.0	+2.9
Kirkuk	LZ	+2.4	+2.3	+2.2	+2.0	+2.1	+1.8	+1.7	+1.8	+1.7	+1.4
Diyala	Diyala	+1.3	−0.1	−0.5	−0.7	−0.2	−0.8	−1.1	−0.4	−0.9	−1.7
Baghdad	Tigris	+27.8	+28.2	+26.4	+23.4	+25.9	+23.4	+19.9	+25.0	+22.4	+18.9
Wasit	Tigris	+18.9	+19.5	+17.2	+13.9	+16.8	+14.1	+10.1	+15.9	+13.0	+8.9
Maysan	Tigris	+10.2	+12.1	+10.8	+8.7	+5.7	+8.5	+6.2	+2.6	+7.7	+5.2
Basrah	Tigris	+7.7	+9.7	+7.4	+4.0	+7.4	+4.9	+0.9	+6.6	+3.9	−0.2
Dhi Qar	Tigris	+2.6	+3.1	+2.3	+1.5	+2.3	+1.7	+0.7	+2.1	+1.4	+0.4

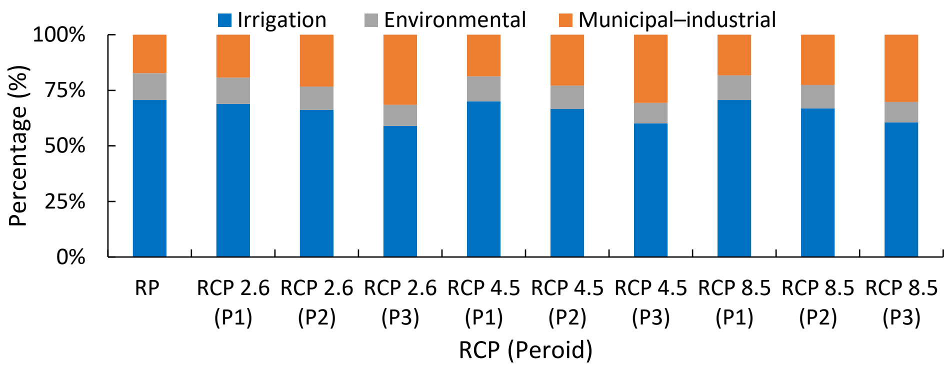

Figure 7. Percentage of water resources distribution among demand sectors considering S3.

Referring to S3, Table 6 shows the percentage of irrigated areas that should be dimensioned to maintain the minimum requirement of flow in the streams for river environmental purposes and to eliminate water stress in Diyala and Basrah. In Diyala (Basrah), the irrigated area should be diminished by lower and upper limits of 8 and 68% (47% under RCP 8.5 and P3) under RCP 2.6, P1 and RCP 8.5, P3, respectively, compared with the irrigated area in the RP.

Table 6. Percentage of diminished irrigated area under S3.

Province	RCP 2.6			RCP 4.5			RCP 8.5		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
Diyala	8 *	23	28	13	35	45	20	38	68
Basrah	-	-	-	-	-	-	-	-	47

* Refer to percentage (%) of irrigated area in RP.

4. Discussion

In comparison with the observations in the RP, RCP 8.5 is the worst expected scenario, with a decline in the projected mean annual streamflow of 13.2, 16.2 and 18.4% during

P1, P2 and P3, respectively. Under the middle, warmest scenario, the streamflow tends to decrease by 10.7, 13.8 and 15.3% for the three future periods. However, the projections show a reduction of around 5% under RCP 2.6. The results of this study are consistent with those of [48,49], indicating an average decline in the water resources of the Tigris River in the range of 8–50% compared with observations recorded in the last three decades. The reduced amounts and spatiotemporal alterations of precipitation patterns play a crucial role in streamflow reduction [50,51]. Moreover, the warmer weather contributes to an increased evapotranspiration rate [52] and loss of large amounts of water from water surfaces such as lakes and rivers [53]. Furthermore, the snowmelt is considered as the main contributor to the streamflow of the northern and eastern parts of the TRB, and, due to climate change, the snow thickness and its spatial extent will decrease in these regions [21].

Baghdad is considered the main water consumer for the municipal and industrial sectors during the RP and in future periods due to the higher residency, manufacturing, trade centers, lifestyle and high number of governmental buildings. Baghdad shared the highest rate of municipal–industrial water consumption with Salah-addin, Kirkuk, Diyala, Wasit and Maysan compared with the northern (Duhok, Ninawa, Erbil and Sulaymaniyah) and southern (Basrah and Dhi Qar) provinces. This can be explained by one or more of the following factors: easy access to water sources [54], lack of or inefficient water meters [55], more water available in streams [56,57] and network leakage [58].

The increase in irrigation and environmental water demands can be explained by the high rate of evapotranspiration [59] and soil moisture depletion [60], factors that are considered natural responses to the increase in surface air temperature related to climate change. Moreover, the impact of climate change in Iraq is indicated by a decrease in precipitation [61], therefore, the contribution of rainfed water will decrease under climate change conditions and this deficiency should be compensated for with irrigation water coming from rivers [62].

This study showed that the municipal–industrial demand will temporally expand compared with the RP due to population growth. This increase in municipal–industrial demand has a negative impact on irrigation and environmental demands because it can become a real threat to sustainably, food security and the ecosystem, especially in the Iraqi Marshlands. The problem will be more complicated due to a decrease in streamflow and an increase in water demand. Improving water use efficiency in irrigation and municipal–industrial sectors can strengthen the resilience of marshlands and support sustainability.

5. Conclusions

Climate change has a negative impact on the streamflow of the TRB due to decreased precipitation, thin snow covers with a lower spatial extent and a high rate of evaporation from water and soil surfaces. Furthermore, water demands will sharply increase due to the impacts of climate change and population growth. The warmer climate in the TRB will increase evapotranspiration, deplete soil moisture and decrease the rainfed, which means necessarily increasing the irrigation water to overcome the lack of precipitation. Population growth is considered the factor that will cause the most stress to future water resources in the TRB. Furthermore, the municipal–industrial demand will increase by three times compared with the RP.

Decreased water resources and increased water demand will pose a real threat to the sustainability of water resources, biodiversity, water security and food security. The worst scenario of the water resources management plan is S1, which involves no change in the current water resources plan. Increased water use efficiency can serve in the sustainable development of water resources, specifically when the most efficient water use plan (S3) is applied. The adaptation plans are restricted by many barriers, such as social, economic, political and institutional barriers. The overcoming of these barriers should be gradually implemented based on the requirements of the current stage. The selection of adaptation scenarios should take into account the applicability, acceptability by stakeholders and suitability (for the climate, topography, soil and type of crop) of these plans.

Other adaption plans can be applied in the TRB which include deficit irrigation and/or micro-irrigation, planting pattern alteration and excluding the most water-consuming crops.

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