Journal of
Water & Climate Change

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Journal of Water and Climate Change Vol 14 No 11, 4261 doi: 10.2166/wcc.2023.534

Water allocation sustainability assessment in climate change: a modeling approach using water footprint and just policy

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ABSTRACT

Climate change has challenged water allocation for food production in water-scarce areas. This fact calls for water reallocation (RA) strategies in basins with dominant agriculture. This study develops a framework combining the SWAT model and water footprint (WF) to evaluate water resource sustainability and improve its indices by fair RA from agriculture. The Karkheh River Basin in Iran was chosen as a study area for verification. Deficit irrigation (DI) was a farm strategy to promote basin sustainability and maintain food security. DI was distributed according to the equality of resources, proposed by Ronald Dworkin, as a just allocation principle. It means irrigated water would be allocated based on an equal water ratio per hectare. Results showed that the basin is currently unsustainable regarding the groundwater (BkWS) and surface flow (BuWS). According to the SSP5-8.5 scenario, the BuWS in the basin increases from 1.12 to 1.22 (9%), and BkWS increases from 2 to 2.15 (7.5%), while GnWS remains relatively constant at 0.99. By Dworkin's principle, DI caused 21-48% reduction in water allocation among five provinces. RA improved the BuWS, GnWS, and BkWS and ensured environmental flow. Climate change reduces 3.5% of food production, with an extra 9% by RA. These reductions would not endanger food security.

Key words: agricultural system, Dworkin principle, reallocation, water–food nexus, water footprint

HIGHLIGHTS

- An integrated approach for water reallocation is proposed by considering hydrological modeling, climate change impacts, water footprint assessment, just water reallocation, food production yields, and security.
- Water footprint and its sustainability indices modeled by the SWAT for climate change conditions.

1. INTRODUCTION

Water resources have been over-allocated in some basins worldwide, which has become a significant concern in water resource management and the environment (Douez *et al.* 2020). In addition, climate change and population growth have increased water demands and intensified this problem, especially in arid and semi-arid regions (Nivesh *et al.* 2023). Therefore, climate change and water scarcity have risked food security and sustainable development in arid regions. It still needs to be determined whether the existing water allocation regime fits these challenges and how it should be reformed (Hellegers & Leflaive 2015).

The fact that the primary consumer of available water resources is irrigated agriculture necessitates water management in the agricultural sector (Doulgeris *et al.* 2015). Governments are setting policies to reallocate water to environmental uses in many major river basins worldwide that were previously developed for irrigation (Bark *et al.* 2014). These reallocation policies are also developed in the form of market-based strategies for other environmental purposes, such as surface or groundwater quality management (Panagopoulos & Giannika 2022, 2023; Souri *et al.* 2023).

Water reallocation (RA) commonly reduces the amount allocated for different demands, especially in the agricultural sector, where it consumes up to 80% of available water (Berbel & Esteban 2019). Meanwhile, pressuring the irrigation sector for adjustments to reallocation policies can be perceived as a conflict with food security. Therefore, sustaining the

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balance between water irrigation and food security is a critical objective (Ren *et al.* 2018). Moreover, agriculture and food security are predicted to be significantly affected by climate change, though the impacts will vary by region and crops (Pilevneli *et al.* 2023). Based on the findings of the ADAPT project in seven basins, it was revealed that the agricultural sector requires effective farm management strategies, specifically in irrigation, to cope with water scarcity and adapt to climate change (Droogers & Aerts 2005). In this regard, deficit irrigation (DI) is widely considered a sustainable strategy to maintain food security and save water in arid and semi-arid regions (Doulgeris *et al.* 2015; Romero *et al.* 2022). DI application rate is 15–50% for different crops, especially wheat and apple (Delavar *et al.* 2020; Babaeian *et al.* 2021).

However, reducing the allocated water may face challenges in the implementation because of potential social consequences. Previous studies have demonstrated that social justice significantly impacts accepting such decisions within society (Syme *et al.* 1999; Hophmayer-Tokich & Krozer 2008). Users will more likely accept RA policies with reduced water allocation if they believe these policies will lead to a just distribution of water resources (distributive justice) through a fair decision-making process, even if it results in economic loss (Jakeman *et al.* 2016). Thus, considering water issues as matters of justice and utilizing distributive justice principles to assess the reallocating scenario is crucial. One of the most relevant distributive justice principles for RA and DI is the equality of resources. In Ronald Dworkin's proposed principle, everyone is responsible for their choices if the water resource is equally shared (Lamont & Favor 2017). A study has yet to be conducted on implementing Dworkin's theory in the allocation/reallocation of water resources. Despite the importance of justice in water resources allocation/reallocation, its concept has attracted little attention among scholars and policy-makers (Thaler 2021). Researchers usually use multi-objective models to allocate water resources in which justice is defined as a utility function or considered by simplified indicators like the Gini coefficient (Hu *et al.* 2016; Roa-García & Brown 2017; Xu *et al.* 2019; Vail Castro 2022), Bentham–Rawls criterion (Xu *et al.* 2019), social welfare, Rawlsian welfare, and Nash scheme (Munguía-López *et al.* 2019; Ochoa-Barragán *et al.* 2021). The shortcomings of Gini and other indicators are that only the inequality principle is emphasized, while justice requires a more extensive picture (Martin *et al.* 2015). In the case of water resource allocation, justice is about (1) ensuring everyone's access to a healthy environment and ensuring the human right to water and (2) satisfying the fair distribution of resources beyond basic needs, which reflects the concept of human development (Movik 2014). One of the principles of modern distributive justice is equality of opportunity and resources. As a first attempt to promote just sustainability (Agyeman & Evans 2004), this study will translate this principle into water reallocation rules to promote just sustainability.

This research initially aims to develop a modeling framework for the sustainability of river basins with dominant agriculture through climate change. Using this framework, we can afterwards reassess current water allocation strategies to be more adaptive against climate change impacts and food security in the future. For these purposes, WF sustainability, as accounting indices, is emphasized coupled with insight on just water redistribution. Dworkin's principle of equality is referred to as the pivotal philosophy for just water reallocation by DI. Therefore, the originality of this research mainly lies in its integrated approach to water reallocation by considering hydrological modeling, climate change impacts, WF assessment, just water reallocation, food production yields and security. Here, the Soil and Water Assessment Tool (SWAT) was used to simulate hydrological processes, production yields, and WF sustainability assessment in both the current and future climate change scenarios. In this regard, the Karkheh River Basin (KRB) was chosen where different stakeholders are potentially in conflict. The developed methodology is explained in detail in the following section. The paper is divided into four sections. Section 2 introduces the proposed meteorology and the KRB as a study area. Section 3 shows and discusses the results in different scenarios and, finally, section 4 concludes the main achievements of this research.

2. METHODS

2.1. Methodology

The method of this research has three main components (Figure 1). The first step focuses on the basin simulation by the SWAT (section 2.1.1). Afterwards, the model's outputs were utilized to evaluate the water footprint sustainability (WFS) indicators (section 2.1.2) and estimate food production per calorie. Simultaneously, in order to predict future streamflow and the impact of climate change on water availability, we utilized precipitation and temperature data from the most reliable CMIP6 Global Climate Models model. This was done specifically for the case study conducted under the very

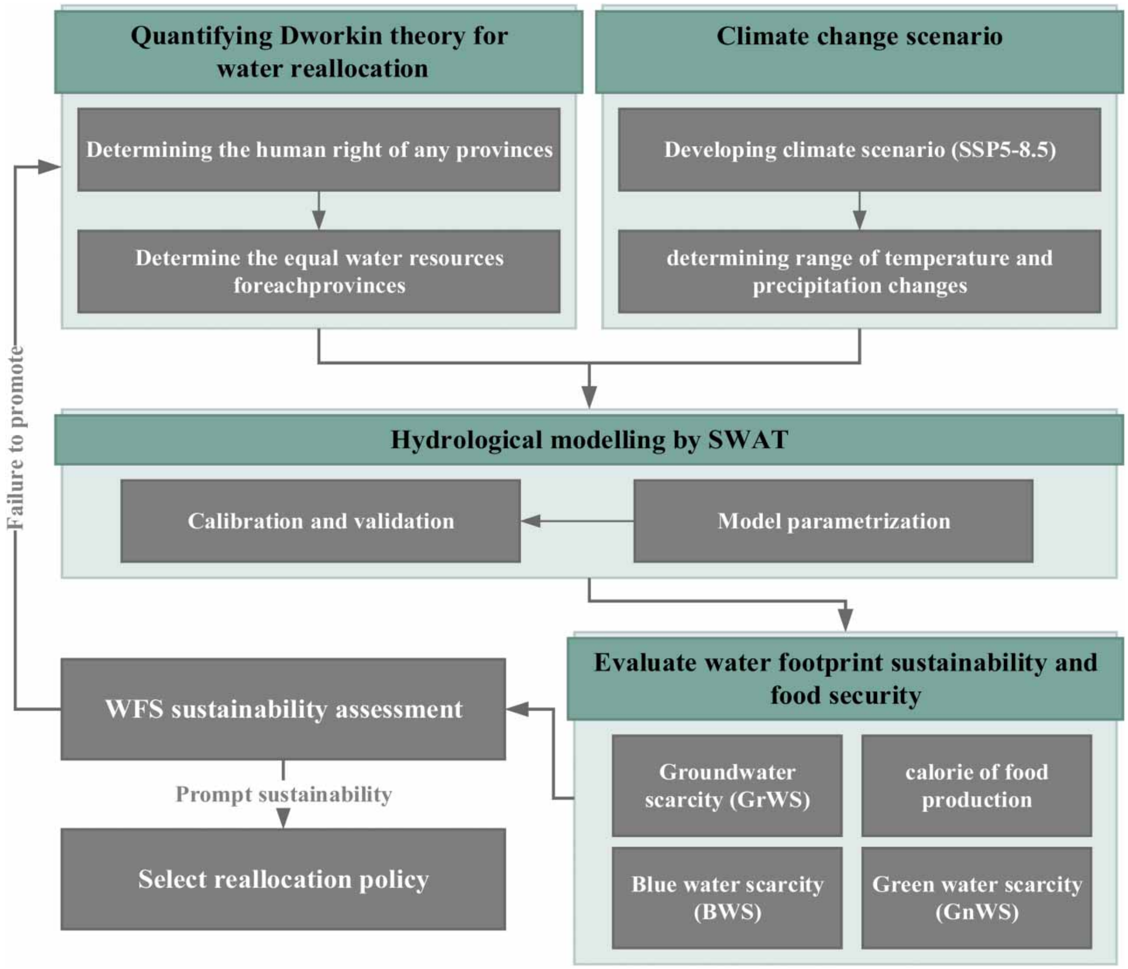


Figure 1 | The overall framework of the methodology.

high greenhouse gas emissions scenario (section 2.1.3). Finally, by these means, the Dworkin theory (Equality of resource) is described for reallocation to increase sustainability in both the current and future scenarios under climate change (section 2.1.4). For the verification of the method, the KRB was selected as the study area where agriculture is the dominant water user.

2.1.1. SWAT model

The SWAT model is an integrated, conceptual, semi-distributed, and continuous-time simulation model (Arnold *et al.* 1998) developed by the USDA Agricultural Research Service. This tool can assess the impact of different climate scenarios and management strategies on water quality and quantity on a basin scale. The primary input of the model includes spatial (e.g., DEM, soil, and land use), hydro-climate, and agricultural management data. In the present study, the SWAT model developed by Delavar *et al.* (2022) is applied for RA assessment (Delavar *et al.* 2022). According to the land use dataset, soil type, and slope properties (Arnold *et al.* 1998) the SWAT model divided the KRB into 153 sub-basins and 1,658 hydrological response units (HRUs) in five provinces as shown in Figure 2.

2.1.1.1. Model parameterization. The SWAT model is used to assess RA scenarios between provinces. Therefore, it was initially set to configure the KRB according to the political and hydrological boundaries. Accordingly, the basin was simulated for the period of 1985–2015. Here, crop management operations, including the plant-growing season, fertilization, irrigation, and harvesting for the six main crops (winter wheat, alfalfa, apple, corn, sugar beet, and tomato)

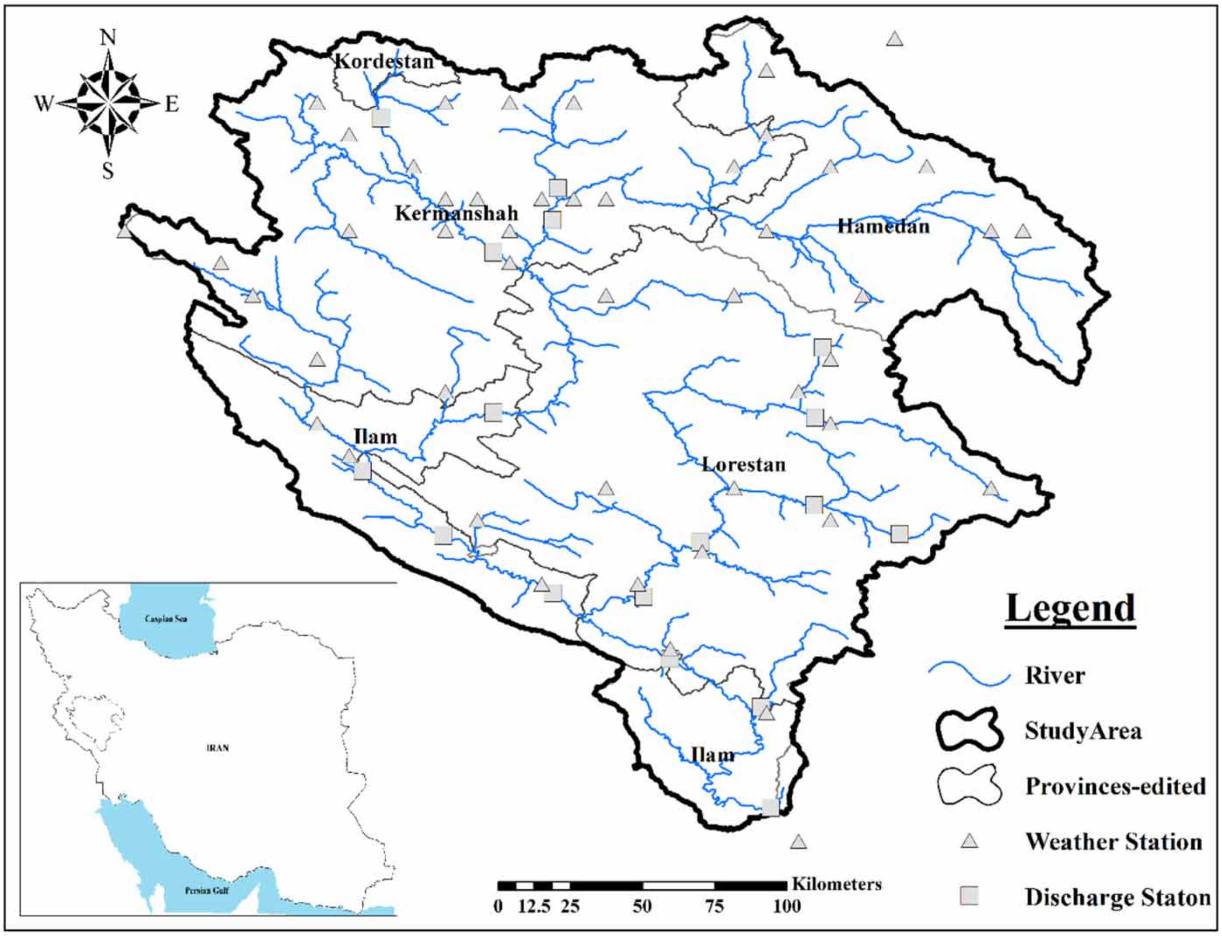


Figure 2 | Location of the Karkheh River Basin (KRB).

were applied to the model. Moreover, some adjustments were made in the SWAT code for appropriate hydrological simulation. Parameters such as manual irrigation efficiency, the interaction between aquifers and groundwater level, and the karst features' simulation are modified in the model. More details about these modifications are explained in previous studies (Delavar *et al.* 2020, 2022).

2.1.1.2. Model calibration and validation. To evaluate the performance of the SWAT model, the sensitivity analysis, calibration, and validation of the model have been carried out with the SUFI-2 algorithm in SWAT-CUP software (Abbaspour 2013). Here, the parameters with the highest impact on the simulated stream flows were defined. If a parameter has relatively considerable t-state value and its *p*-value is close to zero, it would be more effective on and sensitive to stream flows. The results of the sensitivity analysis with the *p*-value and t-state of parameters are presented in Table 1. They show that the SCS runoff curve number (CN2), groundwater parameters (GWQMN), and soil moisture parameters (SOL_Z) are the most influential parameters affecting stream flows in this study.

We used the monthly observed streamflow data of 17 hydrometric stations from 1985 to 2015 for model warmup (1985–1989), calibration (1990–2004) and validation (2005–2015). Table 2 shows the model performance for simulating stream flows in the 17 aforementioned stations using the coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE). R^2 and NSE are more than 0.5 in most stations, showing the model performance is almost satisfactory (Moriasi *et al.* 2007). However, they have reported that other factors, such as quality and quantity of data collection, model calibration procedure, time step, and project scope and scale, might affect the model evaluation (Babaeian *et al.* 2021) as our results are affected by the high numbers of sub-basins (153) and HRUs (1,658).

Table 1 | Summary of sensitivity analysis and *t*-stat and *p*-value of the parameters of the SWAT model

Rank	Parameter	Definition	*t*-Stat	*p*-Value
1	CN2.mgt	SCS runoff curve number	−42.9	0/00
2	GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow	25.21	0/00
3	SOL_Z(..).sol	Depth from the soil surface to the bottom of the layer	4.16	0/00
4	HRU_SLP.hru	The average slope of the hydrological homogeneous unit	−2.20	0.03
5	ALPHA_BF.gw	Base flow alpha factor	−2.16	0.03
6	PLAPS.sub	Annual precipitation gradient	1.45	0.15
7	SLSUBBSN.hru	Average slope length	0.89	0.38
8	SOL_K(..).sol	Hydraulic conductivity of soil	0.83	0.41
9	SOL_AWC(..).sol	Available water capacity of the soil layer	−0.75	0.45
10	GW_DELAY.gw	Groundwater delay	−0.73	0.46
11	SFTMP.bsn	Threshold temperature of snowfall	−0.71	0.48
12	SMTMP.bsn	Threshold temperature of snowmelt	0.62	0.49
13	TLAPS.sub	Annual temperature gradient	0.45	0.65
14	GW_REVAP.gw	Groundwater evaporation coefficient	0.20	0.80

Table 2 | Calibration and validation performance of the KRB model

	Calibration (1990–2004)		Validation (2005–2015)	
Station	R^2	NSE	R^2	NSE
Afarine-Kashkan	0.78	0.69	0.71	0.56
ChamAngir	0.69	0.54	0.59	0.48
ChenarSukhteh	0.78	0.72	0.62	0.16
DarehTang	0.59	0.48	0.64	0.57
Ghorbaghestan	0.75	0.62	0.83	0.7
HeidarAbad	0.76	0.71	0.66	0.62
Holeilan	0.69	0.54	0.14	0.25
Jelogir	0.78	0.71	0.69	0.69
Kakareza	0.63	0.55	0.65	0.53
Karkheh Dam	0.86	0.81	0.87	0.87
NazarAbad	0.7	0.55	0.69	0.63
PolChehr	0.75	0.61	0.74	0.64
PolDokhtar	0.8	0.72	0.73	0.7
PolZal	0.71	0.51	0.52	0.21
SarAsiab	0.87	0.8	0.66	0.6
Seymareh Dam	–	–	0.58	0.67
TangehSazin	0.73	0.68	0.52	0.18

2.1.2. WFS assessment

In this research, the WFS indicator will be applied to analyze the sustainability of the water resources and agriculture system in the current condition and possible future situations by the SWAT model. WFS indicates whether the current water used in the basin ensures the availability of sufficient water for future generations (Pellicer-Martínez & Martínez-Paz 2016). The WF includes blue water footprint, green water footprint, and grey water footprint (Hoekstra *et al.* 2017). According to the purpose of this research, the sustainability of green, blue, and groundwater will be assessed.

Besides, WFS can assess the water resources sustainability of agricultural systems based on the indicators of green water scarcity (GnWS), blue water scarcity (BWS), and groundwater scarcity (GrWS) (Babaeian *et al.* 2021; Jamshidi *et al.* 2022) which are shown in relations 1, 2, and 3, respectively. Suppose the proportion of these equations is higher than 1. In that case, the use of WFS in the basin is full and unsustainable, while with lower values than one, the water availability in the basin would be enough for the current use of the basin.

$$\mathrm{GnWS}[x,\,t] = \frac{\sum \mathrm{WF}_{\mathrm{green}}[x,\ t]}{\mathrm{WA}_{\mathrm{green}}[x,\,t]} \tag{1}$$

$$\mathrm{BuWS}[x,\,t] = \frac{\sum \mathrm{WF}_{\mathrm{blue}}[x,\ t]}{\mathrm{WA}_{\mathrm{blue}}[x,\,t]} \tag{2}$$

$$\mathrm{BkWS}[r] = \frac{\sum_{t=1}^{N} \mathrm{EX}_{\mathrm{Ground}}[r,\,t]}{\sum_{t=1}^{N} \mathrm{WA}_{\mathrm{blue-ground[r,t]}}} \tag{3}$$

In these equations, $\mathrm{WF}_{\mathrm{green}}$ is the agricultural green water footprint (calculated by Equation (4)), $\mathrm{WA}_{\mathrm{green}}$ is the green water availability (Equation (5)), $\mathrm{WF}_{\mathrm{blue}}$ is the agricultural blue water footprint (Equation (6)), and $\mathrm{WA}_{\mathrm{blue}}$ is the blue water availability (Equation (7)) in a specific time (t) in each sub-basin (X). In addition, $\mathrm{EX}_{\mathrm{ground}}$ is extractions from the aquifer (r); $\mathrm{WA}_{\text{blue-ground}}$ is recharged to the aquifer (r).

$$\mathrm{WF}_{\mathrm{green}}[x,\ t] = \sum (\mathrm{ET}_{\mathrm{green}} \times \mathrm{Area} \times 1,000) \tag{4}$$

$$\mathrm{WA}_{\mathrm{green}}[x,\,t] = (\mathrm{ET}_{\mathrm{green}}[x,\,t] + \mathrm{SW}_{\mathrm{green}}[x,\,t]) \times \mathrm{Area} \tag{5}$$

$$\mathrm{WF}_{\mathrm{blue}}[x,\,t] = \sum (\mathrm{ET}_{\mathrm{irr}} \times \mathrm{Area} \times 1,000) - \mathrm{WF}_{\mathrm{green}}[x,\,t] \tag{6}$$

$$\mathrm{WA}_{\mathrm{blue}}[x,\,t] = (\mathrm{PCP}[x,\,t] \times \mathrm{Area} \times 1,000) - (\mathrm{WA}_{\mathrm{green}}[x,\,t] + \mathrm{EFR}[x,\,t]) \tag{7}$$

Here, $\mathrm{ET}_{\mathrm{green}}$ is direct evapotranspiration of precipitation, $\mathrm{SW}_{\mathrm{green}}$ is soil moisture from precipitation, $\mathrm{ET}_{\mathrm{irr}}$ is evapotranspiration from irrigation and precipitation together, PCP is the total precipitation, and EFR is environmental flow requirements, which is the aggregate of 1,283 million cubic meters required for Hour-al-Azim (Roozbahani *et al.* 2011) and the primary environmental flow of the river in the period t obtained by the Montana method.

2.1.3. Climate change scenarios

This section projected temperature and precipitation data as output variables fed into the SWAT model. It is needed for future streamflow simulations and to quantify and project the effects of climate change on the future availability of water. For this purpose, the best model of the CMIP6 GCMs (IPSL-CM6A-LR) was used to analyze precipitation and temperature for the near future (2021–2050) under Shared Socioeconomic Pathways (SSPs) 5-8.5. The SSP5-8.5 scenario is high-force, representing the combination of high social vulnerability and high radiative forcing, and it is the only path to achieve the man-made radiative forcing level of 8.5 W m^{-2} by 2100 (Sun *et al.* 2022). The criteria for selecting the GCMs model was based on their highly acceptable performance in the previous studies investigating climate change impacts on the KRB (Ashraf Vaghefi *et al.* 2015; Fereidoon & Koch 2018). Downscaling the GCMs outputs and generating weather variables was accomplished by the LARS-WG weather generator (Semenov *et al.* 2002). The model's performance was evaluated at two synoptic stations, Ravansar and Khoramabad (Figure 1), from 1990 to 2015.

2.1.4. Dworkin theory in equality of resource

The Principle of Natural Resource Equality means that everyone has a claim to an equally valuable share of Earth's natural resources. Ronald Dworkin proposed the theory of equality in resources as one of the first and most essential theories of Luck egalitarianism (Dworkin 1981a, 1981b). Dworkin proposed that people begin with equal resources but be allowed to end up with unequal economic benefits due to their own choices (Lamont & Favor 2017). Accordingly, after equal distribution of resources, if individuals (farmers in this study) are disadvantaged because of someone's choices, it cannot be included as an injustice despite its inevitable inequality in welfare (Barry 2017). Therefore, treating people as equals ensures that income and wealth distribution at any given moment is ambition-sensitive but not endowment-sensitive. Regarding sensitivity to 'ambitions,' Dworkin argues that provided people have an 'equal' starting point (in Dworkin's case, resources), they should live with the consequences of their choices (Lamont & Favor 2017). Concerning 'endowments,' Dworkin proposes a hypothetical compensation scheme in this scheme, people who are unlucky in the 'natural lottery' and disadvantaged in the natural distribution provided before equal sharing of resources (irrigation water).

In this study, environmental needs are considered disadvantaged in the natural distribution of resources. Notably, the environment is regarded as the most vulnerable sector with the highest priority for water allocation. Subsequently, the ratio of available water for irrigated agriculture, subtracted by the environmental need, to the total area of irrigated fields in each province (EWR) is calculated as Equation (8). The SWAT outcomes estimate the amount of currently allocated water for the agricultural sector in each province.

$$\mathrm{EWR} = \frac{\sum_{i=1}^{n} (\mathrm{WA}_{\text{irrigated agriculture}}[i] - Eflow[i])}{\sum_{i=1}^{n} \mathrm{Area}_{\text{irrigated farmland}}[i]} \tag{8}$$

where $\mathrm{WA}_{\text{irrigated agriculture}}$ is water for irrigated agriculture of each province (i), E_{flow} is the environmental need, and irrigated farmland is the area of irrigated agriculture.

Regardless of planting type, each farmer receives equal water for one hectare of irrigated land based on Equation (8) and Dworkin's principle in the starting point. Therefore, farmers can each make a unique profit by choosing their desired planting and irrigation methods. This inequality in economic benefits, which results from how to use equally allocated resources initially, is fair. In addition, according to the Dworkin principle, the need of the environment as the disadvantaged sector should be met before reallocating water to irrigated agriculture.

2.2. Study area

The KRB is Iran's third-largest and most productive river basin in the southwest of Iran. The KRB is located between a longitude of 46°06 to 49°10 E and a latitude of 30°58 to 34°56 N that approximately covers 42,267 km^2 surface area. This basin administratively includes seven provinces of Kurdistan, Kermanshah, Hamadan, Ilam, Lorestan, Markazi, and Khuzestan (Figure 2). Its highest and lowest points are about 3,623 m and 182 m above sea level. The long-term annual average precipitation in the basin varied from 300 mm in the arid region of the south to 800 mm in the semi-arid north (Fereidoon & Koch 2018). About half of the precipitation falls in the cool months of January–March, and the warmest months of June–September receive less than 2% of the total precipitation.

The Karkheh River is the main river of the basin that originates from the central zone of the Zagros Mountains and flows into the Hour-al-Azim wetlands on the border with Iraq. The KRB is one of the most productive agricultural areas known as the food basket of Iran, making up 9% of the irrigation fields of Iran and producing about 10% of the country's wheat (Ashraf Vaghefi *et al.* 2015). However, the water use efficiency in this section is the most challenging issue. Significant decline in the Karkheh River discharge in recent years increases concerns for drinking water and agriculture and the environmental needs of the downstream areas (Delavar *et al.* 2022). Accordingly, the KRB is a notable example of an agriculturally heavily exploited basin with typical water challenges faced similarly in other regions worldwide (Fereidoon & Koch 2018).

3. RESULTS AND DISCUSSION

3.1. Basin sustainability

Basin simulation by the SWAT model could provide a framework for calculating blue, green, and black water scarcity. Results showed that GnWS is relatively constant and sustainable in the whole area (<1), whereas BuWS is unsustainable (>1) for the basin on average, as well as Kurdistan and Hamedan provinces (Figure 3(a)). Moreover, BkWS is unsustainable for the whole basin and all provinces without exception. It verifies that current water management strategies impair groundwater. Based on the climate scenario of SSP5-8.5, BuWS, and BkWS are slightly increasing for the next decades (Figure 3(b)). For example, the average BuWS of the basin increases from 1.12 to 1.22 (9%), and its BkWS increases from 2 to 2.15 (7.5%), while GnWS remains rather unchanged at $0.99 < 1$. It shows that current strategies on irrigated farmlands will intensify the sustainability problems of the basin. Some provinces, such as Ilam and Kurdistan, would be highly exposed to climate change, with 28.3

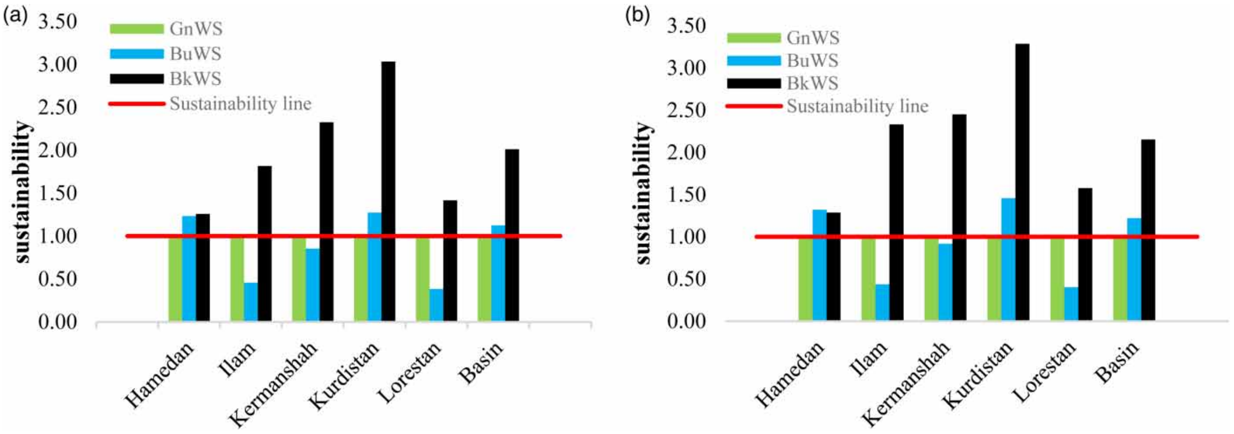


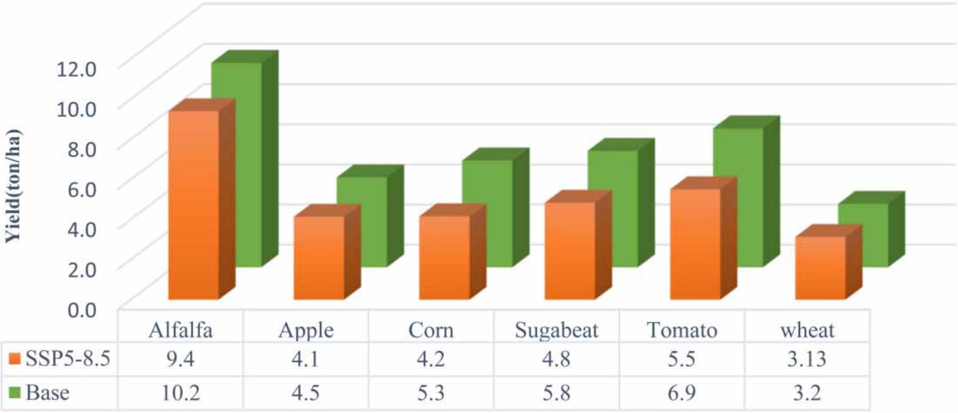
Figure 3 | BuWS, GnWS, and BkWS of the basin and provinces in (a) current and (b) climate change scenarios.

and 14.4% increases in BkWS and BuWS, respectively. In contrast, some provinces, such as Kermanshah, with 6–8% WS variations, can stand more sustainably against climate change conditions.

Climate change conditions also have adverse impacts on the yields of agricultural products. Simulation results indicated that the production yields would be decreased. Corn, tomato, and sugar beet among the crops would experience the highest reduction, up to 21, 20, and 17% by the SSP5-8.5 scenario, respectively (Figure 4). On the contrary, other crops, including apple and wheat, have the least yield variations, about 9 and 2%, respectively. Based on calorie calculations, the average nutrition produced in the basin would be decreased by only 3.5% in SSP5-8.5. This is due to the fact that dominant nutritious products, like wheat, are rain-fed, and GnWS is rather constant. In other words, provinces with more dominant rain-fed crops (upstream provinces) would have better food security during climate change in this area.

3.2. Water reallocation

The Dworkin equality of resource theory was chosen as the basis for just water reallocation to improve basin sustainability. According to this principle, farmers should equally have access to irrigated water per land area (m^3/ha). It should be noted that this water reallocation for agriculture should be carried out after allocating the required drinking (250 MCM) and minimum ecological water (1,600 MCM) as a human right to water. After satisfying the drinking and environmental needs, the agricultural sector in the basin will face a decrease in allocated water. The next step includes reallocating agricultural water based on the equality of resource principle (equal water per hectare of farmland). This may result in reduced allocated water for some provinces, while others may receive more water for agriculture.



	Alfalfa	Apple	Corn	Sugabeat	Tomato	wheat
🟧 SSP5-8.5	9.4	4.1	4.2	4.8	5.5	3.13
🟩 Base	10.2	4.5	5.3	5.8	6.9	3.2

Figure 4 | Agricultural production yields per current and climate change scenario of SSP5-8.5.

Figure 5 indicates the allocated water of provinces (MCM) in the current situation (Base) and after reallocation (RA) under the fossil-fueled development scenario in the future (SSP5-8.5). Here, Kermanshah experiences the highest reduction in allocated water from 799 to 565 MCM (234 MCM), whereas Kurdistan experiences the least reduction from 28 to 17 MCM (11 MCM). Water reductions in Kermanshah, Lorestan, Ilam, Kurdistan, and Hamedan equal 29, 21, 48, 39, and 22%, respectively. Accordingly, the average water withdrawal in the agricultural sector of the KRB reduces from 1,647 to 1,182 MCM, saving 28% of water resources for other sectors like the environment.

By the aforementioned water reallocation rule, the BuWS and BkWS of the basin improved by 15 and 17% in the current condition (Figure 6(a)). These indicators also recover about 22% under climate change conditions (Figure 6(b)). Thus, the basin's average BuWS, GnWS, and BkWS reach 0.99, 0.95, and 1.67. Just water reallocation based on the Dworkin principle can improve basin sustainability, but BkWS is still above 1 (unsustainable).

3.3. Water–food nexus

Although the water reallocation strategy (RA) under the SSP5-8.5 scenario improved BuWS and BkWS, the agricultural production yields decreased due to less irrigation. The impact of RA on yield reduction can be better compared to climate change conditions. Figure 7 in SSP5-8.5 without RA shows that the production reduction compared to the base ranges between 1.1% (wheat) and 21.9% (corn) in this basin. However, with the application of RA aimed at increasing sustainability, crop yields reduce between 9.8% (wheat) and 33.3% (corn). It means that RA could improve water saving at the cost of losing nutritious production. This conclusion implies that WF sustainability indices only consider water scarcity and do not necessarily include other sustainability pillars, such as the economy or society. Therefore, using the term sustainability for these indices may need some clarification.

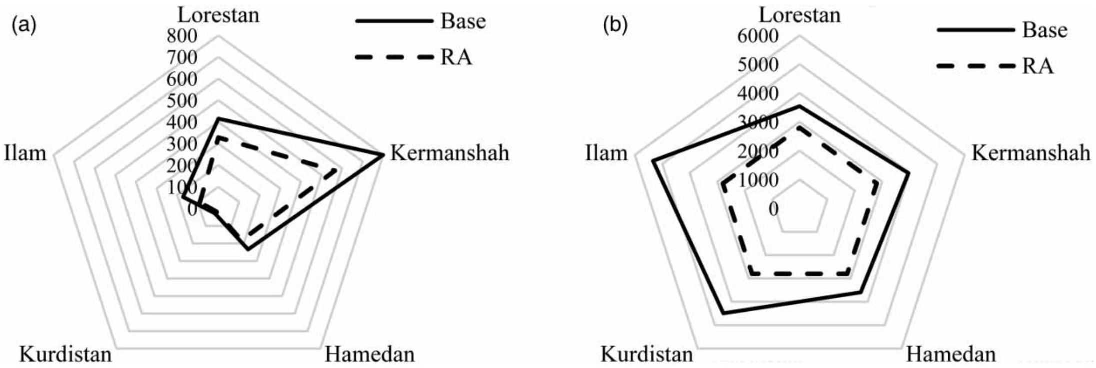


Figure 5 | (a) WF (MCM) and (b) its value per area (m^3/ha) in the current (base) and water reallocation (RA) conditions.

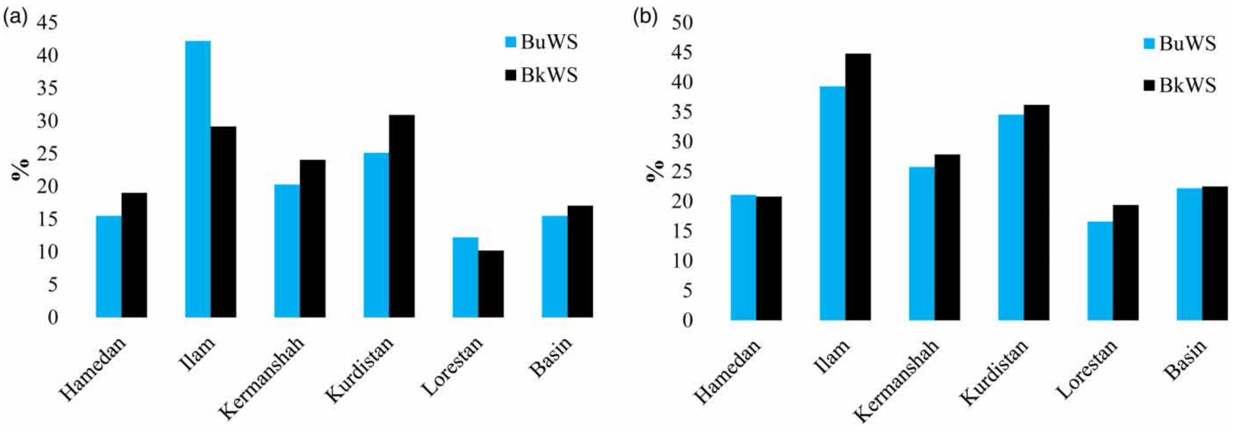


Figure 6 | BuWS and BkWS of basin and provinces after reallocation in (a) current and (b) climate change scenario.

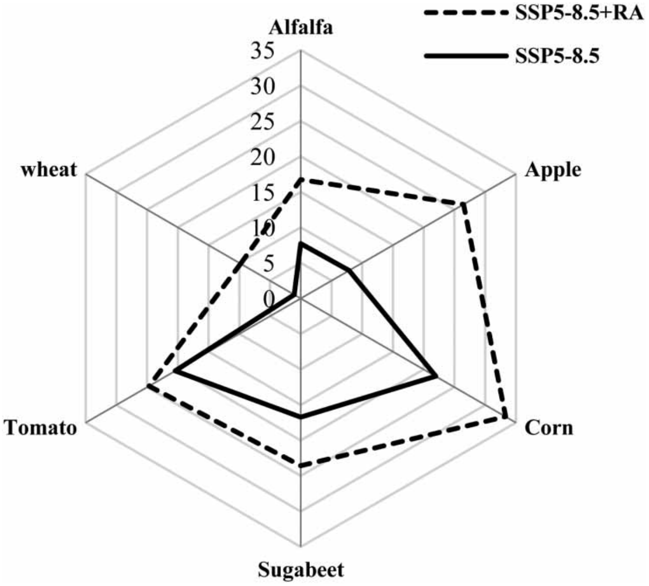


Figure 7 | Production yield reduction (%) of crops in the climate change scenario (SSP5-8.5) with and without water reallocation in comparison with the base scenario.

It should be noted that the total produced calories in the current water allocation is approximately 37.56 Mcal/ha. By SSP5-8.5 without and with RA, this value is 36.24 and 32.83 Mcal/ha, respectively. It means that climate change reduces 3.5% of overall production, and RA adds more reduction by 9%. Nevertheless, these reductions may not endanger food security in this basin which equals 9 Mcal/ha. Therefore, RA would not be a real threat to food security, but future studies should consider revising WFS indices. For example, the index of food environmental footprint (FEF) is one step forward (Jamshidi & Naderi 2023), considering the combined effects of water pollution and nutritious production with a water–food nexus.

4. CONCLUSION

This study used the SWAT model to evaluate the three sustainability indices of blue, green, and black water scarcity of six agricultural productions in the Karkheh basin in three scenarios of current climate change (SSP5-8.5) and water reallocation policy (RA). According to the results, we can conclude that:

- Water footprint and its sustainability indices (BuWS, GnWS, and BkWS) can be modeled by the SWAT in different conditions, like climate change. They can provide an accounting framework to outline and compare the basin status with a water conservation perspective.
- BkWS is the main challenge of all provinces in the Karkheh basin (>1), while BuWS is also critical for some provinces. These two indices get worse by climate change, while GnWS remains rather constant. Here, corn, tomato, and sugar beet experience the highest reduction, up to 17–21%, which makes them vulnerable to production in climate change concerns. In Iran and the KRB, only corn is considered a strategic crop for self-sufficiency, while the others are not.
- The Dworkin principle is a recommended rule for fair water reallocation, allowing greater water allocations from agriculture to environmental purposes. WF per land area is equalized for all stakeholders here, in provinces. RA could improve basin sustainability in both the current and climate change scenarios. Here, it could also ensure the available water for drinking and ecological purposes. Under RA policy, water withdrawal in stakeholders (five provinces) was reduced by 21–48%, making BuWS becomes sustainable (<1), while BkWS remains unsustainable (>1).
- Despite improving water sustainability in the basin by RA, the production yield would be adversely influenced. Consequently, overall food production decreases. According to a research study, climate change reduces 3.5% of overall production, and RA adds more reduction by 9%. However, this reduction does not pose a threat to food security in this particular case. As food security is a crucial objective for sustainability, conducting further investigations into the impact of RA rules on food security in other regions is crucial.

This research provides a practical framework for water reallocation that promotes sustainability for both present and future generations. This integrated approach can be applied to regions that face environmental challenges and dominant agriculture. However, it is crucial to consider the economic implications of transferring water from agricultural to urban and industrial regions. Any significant changes to water reallocation could impact local and regional economies and the global food supply and demand. Furthermore, exploring different distributive justice principles, sustainability of grey water footprint, pollution reduction, and multi-objective optimization is recommended when studying water reallocation.

ACKNOWLEDGEMENT

Iran Water Resource Management Company partially supports this study under contract No. S.0012.1401 with University of Tehran.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 7 August 2023; accepted in revised form 17 October 2023. Available online 28 October 2023