Estimation of Blue and Green Water Potentials of Türkiye under Global Climate Change Effects

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Abstract

This study analyzed the impact of global climate change scenarios on the water resources of Turkiye by means of various climate and hydrological simulations projected for this century. An integrated approach was used by coupling regional climate models and a semi-distributed hydrologic model to assess the climate change impacts. A regional climate model, that is the output of 3 global models (HadGEM2-ES, MPI-ESM-MR and CNRM-CM5.1), has been conducted with RCP4.5 & RCP8.5 emission scenarios for whole the country at the watershed-scale with a resolution of 10x10 km. Hydrological simulations were conducted by using the Soil and Water Assessment Tool (SWAT) Model to determine the variation of surface and groundwater resources based on climate change projections. Blue water flow (water yield + deep aquifer recharges), green water storage (soil water), and water surplus/deficit projections have been conducted considering the current and projected status for water-consuming sectors of domestic, industry, agriculture, and ecosystem services. Results attained were further evaluated through statistical methods regarding blue water flow and green water storage potential of the country. The main purpose of the study was to aid the legal authorities, and decision-makers in prioritizing the environmental measures to be taken for mitigation of climate change impacts on Turkiye in the long- run. The work was the first country-wide hydrological modelling study through globally accepted climate change scenarios.

Keywords: Turkiye; Hydrology; Water budget; Climate change; Mediterranean Region

1 Introduction

Based on the existing monitoring data and climate projections, scientists highly agree on the fact that water resources have the potential to be strongly affected by climate change in the long-run (Arnell, 2004; Arnell et al., 2011; IPCC, 2013). Meeting water resource requirements for various water-dependent sectors has become a crucial challenge especially in arid and semi-arid regions of the world (Shamir et al., 2015) due to the increased water demand in connection with population growth. Therefore, the quantitative representation of water resources under the changing environment is an essential tool towards selecting the appropriate sectoral-based mitigation measures regarding climate change adaptation efforts. Mediterranean Region has been identified as one of the hot-spot regions of the world suffering from water scarcity and irregular water availability (Giorgi, 2006; Hoerling et al., 2012; Lionello, 2012). Besides, future climate simulations raise a concern regarding the substantial changes in the regime of climatic variables and water availability (Kundzewicz et al., 2008; Shen et al., 2010; Koutroulis et al., 2018). Blue and green water terminology approach put forth initially by Falkenmark and Rockström (2006) is considered as one of the convenient paradigms of water resource management (Veettil & Mishra, 2016). Blue water is defined as the amount of flow that is stored in lakes, reservoir or aquifers, whereas the water stored in soil and vegetation canopy is classified as green water (Falkenmark & Rockström, 2006; Rockström et al., 2009). Blue water supplies the demand for human consumption (Rodrigues et al., 2014), and green water is critical for crop yield (Liu et al., 2009), especially in rain-fed agriculture (Schuol et al., 2008). Blue and green water paradigm has been used to quantify water resources in numerous climate change modelling studies considering its importance for water resource planning extending from regional to global scale. For example, Gerten and Heinke (2011) compared water availability and water requirements for food production in terms of green water at a global scale. Huang et al. (2019) also evaluated the global green water consumption under climate change impacts. Faramarzi et al. (2013) and Chiarelli et al. (2016) have built a continental-scale model to evaluate both blue and green water of Africa. Moreover, numerous studies were conducted on regional-scale to predict the blue and green water under climate change in the Black Sea Catchment (Rouholahnejad-Freund et al., 2017), the Ratiran River Basin, USA, (Giri et al., 2018), the Upper Narmada Basin, India (Pandey et al., 2019). Along with the changing climate, quantifying a country's water resources has become crucial for the long-term strategic planning. In this context, plenty of country-wide water availability modeling studies was conducted. Abbaspour et al. (2009) assessed the freshwater availability of Iran as a semi-arid country. White et al. (2015) utilized the SWAT model to predict the hydrologic budgets for the USA, and the usage of blue and green water resources by four commodity crops. The future food security of China was evaluated by means of the green and blue water approach by Huang et al. (2015).

Turkiye is a trans-continental country located in the Mediterranean Region on both continents of Asia and Europe. The semi-arid country has a total area of ~780,000 km^2 with a population of ~85 million as of year 2021. It has considerably high environmental gradients; such as changes in elevation, biogeographical diversity, and several climate zones that differ distinctly. Reservoirs mostly filled by surface water are used to supply the water demand from all water-using sectors such as domestic, agricultural, industrial, and ecosystem services. Managing water resources in such a diverse geography requires a more holistic approach. Therefore, considering the impacts of climate change on the blue and green water along with sectoral water demands is a key issue to be considered in detail towards sustainable water management in Turkiye. Climate change has so far been studied over the country in numerous studies with different contexts and aims. Regional climate models were used by scientists and academicians (Onol & Semazzi, 2009; Bozkurt et al., 2012; Ozturk et al., 2013; Onol & Unal, 2014) in order to analyze the temperature and precipitation regimes under climate change impacts at a national-scale. Another country-wide study conducted over Turkiye by Sen et al. (2015) indicated a decrease in precipitation that will result in a reduction in the water resources, which will in turn, negatively affect the amount of useable water in the coming decades. Numerous studies have also been conducted to evaluate the impacts of climate change at regional-scale throughout the country (Bozkurt & Sen, 2013; Selek & Tuncok, 2014; Yürekli, 2015; Sen, 2019; Yilmaz et al., 2019; Gorguner et al., 2019). These studies made valuable and significant contributions to climate change impacts on hydro-climatic conditions in Turkiye.

The work holds valid to be the initial hydrological modelling study covering all of Turkiye through globally accepted climate change scenarios with the estimation of blue and green water availability.

Even though the current literature provides valuable information on basin-scale water management strategies, climate change impacts with respect to different aspects of sectoral water use throughout the country or inter-basin water transfers are still lacking. This study is the first attempt conducted to fill this important gap in literature. It also provides a comprehensive overview on the current water resources of Turkiye. The main goal of this study is to evaluate the changes in blue water flow and green water storage potential of Turkiye in connection to climate change projections, and water requirements of domestic, agricultural, industrial, and ecosystem sectors. In order to fulfil this purpose, an integrated approach is used by coupling regional climate models and a semi-distributed hydrologic model in order to assess the climate change impacts as a whole.

2 Material and Methods

2.1 Study Area

Turkiye (Figure 1) is distributed into 25 hydrological river basins (watersheds). Table 1 compares the gross/net and sectoral water distribution condition of the country as of year 2015.

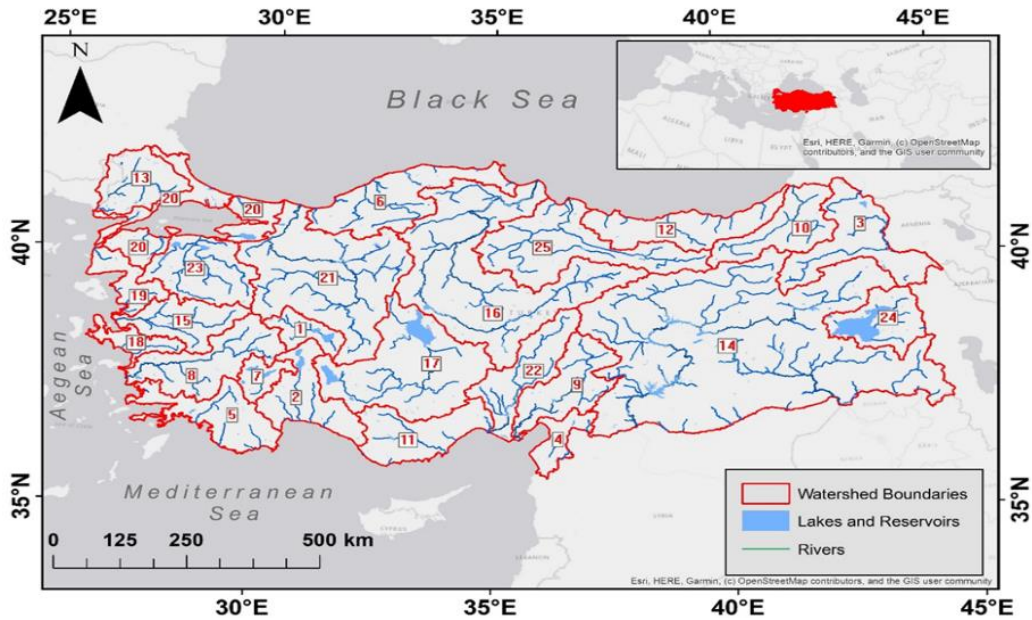


Fig. 1: Watersheds and mainstream networks of Turkiye

Table 1: Total Water Distribution Of Turkiye (2015)

Water Distribution	Turkiye (25 Watersheds)		
	Groundwater	Surface Water	Total
Gross Water Potential (million m^3/year)	19,447	186,050	205,497
Net Water Potential* (million m^3/year)	14,757	93,480	108,237
Drinking Water Allocation (million m^3/year)	2,914	7,284	10,198
Industrial Water Allocation (million m^3/year)	2,195	668	2,863
Agricultural Water Allocation (million m^3/year)	7,562	22,531	30,093
Total Water Allocation (million m^3/year)	12,671	30,483	43,154
Drinking Water Distribution (%)	23		
Industrial Water Distribution (%)	7		
Agricultural Water Distribution (%)	70		
Water Surplus (million m^3/year)	(+) 65,082		

* Technically and economically available water amount

2.2 Modelling Network

Within the scope of climate projections, outcomes of 3 global models selected from CMIP5 archive and RCP4.5 and RCP8.5 release scenarios and RegCM4.3 regional climate model forming the basis of the 5th Evaluation Report of Intergovernmental Panel on Climate Change (IPCC, 2014) were studied. A total of 8 parameters and 17 climate indices representing extreme (weather) conditions were conducted at basin-scale through model simulations covering all the watersheds of Turkiye until 2100. The studied parameters were projected as seasonal and annual averages for 10 and 30-year intervals based on the reference period accepted as of 1971-2000. Climate change simulations at 10x10 km resolution has been obtained by using start and limit conditions (ERA-40 reanalysis data) (Uppala et al., 2005) for the reference period. Followingly, the reference period climate simulations were performed with 10x10 km resolution of HadGEM2-ES, MPI-ESM-MR and CNRM-5.1 global climate models. Comparisons were made among the simulations performed with regards to the observation data of the reference period, and the simulations of the global model in order to determine the bias level of the global model. Simulations based on RCP4.5 and RCP8.5 representational concentration routes for 3 global models, and climate simulations with RegCM4.3 regional climate model for the projection period of 2015-2100 have been obtained (CCIWRT, 2016).

In the study, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has been used as a precipitation-runoff model to simulate hydrological process as well as to estimate blue and green water budget of Turkiye. SWAT model, which is developed by Texas University Department of Agricultural Engineering, is a continuous-time and physically based semi-distributed model (Neitsch et al., 2011). In the model, the hydrological balance is calculated as:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

SW_t is the soil water content at time t (mm·H_2O)

R_{day} is the precipitation on day I (mm·H_2O)

Q_{surf} is the surface runoff on day i (mm·H_2O)

E_a is the evapotranspiration on day i, (mm·H_2O)

w_{seep} is the amount of the seepage to the vadose zone from soil profile on day i (mm·H_2O)

Q_{gw} is the amount of return flow on day i (mm·H_2O)

SW_0 is the initial soil water content

Building a hydrological model for an entire country with an area of 783,562 km^2 is a complex task that needs extensive data. In the study, the topography of the country was obtained from Space Radar Topography Mission (SRTM) data sets, where 90x90 m resolution Digital Elevation Model (DEM) was used. Land use data were obtained from the CORINE 2012 database, while the soil data was compiled from the Food and Agricultural Organization (FAO) global data sets. Meteorology data were obtained from the weather database (http://globalweather.tamu.edu/). The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) was completed over the 31-year period from 1979 through 2009 for the meteorological data. The ArcSWAT interface was used to delineate a total of 25 river basins in Turkiye, and their sub-basins generate the necessary input files, whereas independent MATLAB based scripts were developed and used to manipulate the SWAT inputs for fine-tuning and for processing the model outputs.

Hydrogeology and irrigation areas for hydrological response unit (HRU) generation as well as irrigation and surface water-groundwater interaction were thoroughly considered to be spatially accurate. Since most of the data (such as crops, water supply, and irrigation) have been based on administrative units (mostly provinces in Turkiye), provinces were also used to generate the HRUs. Moreover, 925 aquifers throughout the country were identified with their real attributes (such as static storage, dynamic storage as deep aquifer recharge), the ratio of confined to unconfined aquifer components, aquifer depth, etc. were identified based on 1/500,000 scaled geological and hydrogeological maps of Turkiye. The related HRU parametrization was carried out based on this information. In addition, irrigation estimates on major irrigated areas of Turkiye (more than 2,400 areas covering ~55,000 km^2) were led and utilized as well. The simulations were set up for the period of 1979-2009, where the years between 1979-1989 (end of years) were considered as the warm-up period of the model. The simulation results for 1990-2009 were averaged over time, and compared with the water budget of Turkiye obtained from State Hydraulic Works (DSI). A general overview of the modelling scheme is depicted in Figure 2 in order to summarize the models and data used.

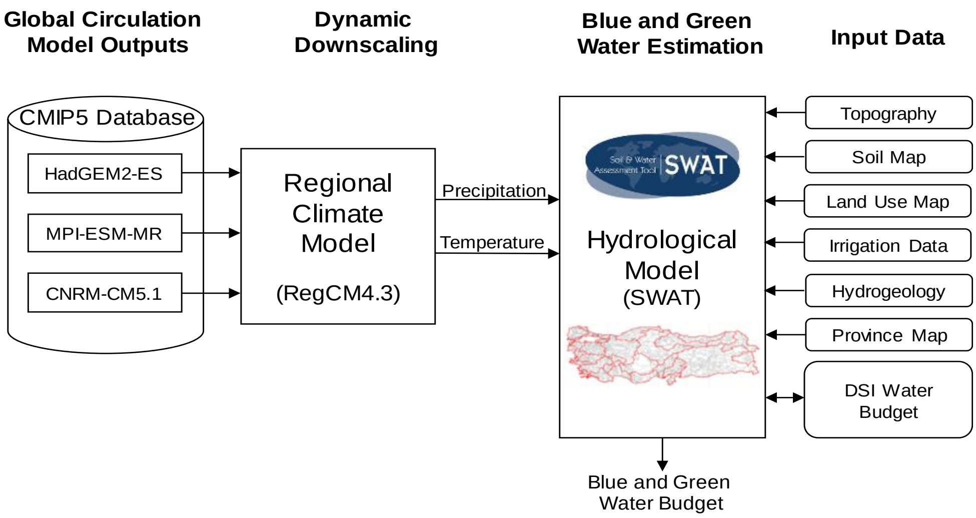


Fig. 2: Blue and green water estimation framework used in the study

At the time of this study, parallel versions of SWAT utilizing multiple CPU power were not available. The feasible solution was to divide the large Turkiye model on SWAT to 25 smaller intergrated watershed models. This was conducted enhancing the MATLAB based tool (Cerkosova et al., 2018). SWAT process results the surface water (water yield), and groundwater (deep aquifer recharge) potentials of all 25 river basins were calculated and compared at the end of the calibration process with the datasets obtained from DSI (Table 2). The two most significant components of the water budget, total flow (water yield) and groundwater potential (deep aquifer recharge), as the two most significant components of the water budget, both showed a relative deviation of + 2.3% from the reference period (1971-2000) of the SWAT model projections for Turkiye (Table 2). It has proven that the hydrological model can be used safely and accurately in climate change projections regarding all 25 river basins as well as the overall country.

Table 2: Comparison of hydrologic model estimates with the reference period for Turkiye

Water Potential Component	Reference Period (1971-2000) Existing Data (million m^3/year)	Hydrologic Model Estimates for the Reference Period (million m^3/year)	Relative Error (%)
Water Yield	186,050	190,383	+2.33
Deep Aquifer Recharge	19,717	20,141	+2.15
Total Blue Aquifer Flow	205,767	210,524	+2.31

3 Results and Discussions

Within the scope of this study that is based on the reference period observation data obtained from DSI (1971-2000), the blue water potential and its components have been provided as summarized in Table 3. Accordingly, Turkiye's blue water potential as calculated for the reference period with the hydrological model is given as 108.5 km^3 (instead of the total 112 km^3). Wherein the groundwater reserve gross-to-net ratios have been taken within the range of 45-99%, each taken specific to the watershed (country average: 75%) in order to calculate the groundwater potential (net deep aquifer recharge) for the overall country.

On the other hand, the gross-to-net ratio for river flows is taken as 50% for all the watersheds as Turkiye's average, in order to estimate the total surface water potential (net blue water yield). It should be noted the net amount is the technically and economically available water amount that can be retrieved from the natural resources.

Table 3: Water potential values of Turkiye obtained through hydrological modelling for the reference period

Components	**Values (km^3)**
Gross Water Yield (River Flows)	186,050
Net Water Yield	93,480
Gross Deep Aquifer Recharge	19,447
Net Deep Aquifer Recharge	14,757
Total Gross Blue Water Flow	205,497
Total Net Blue Water Flow	108,237

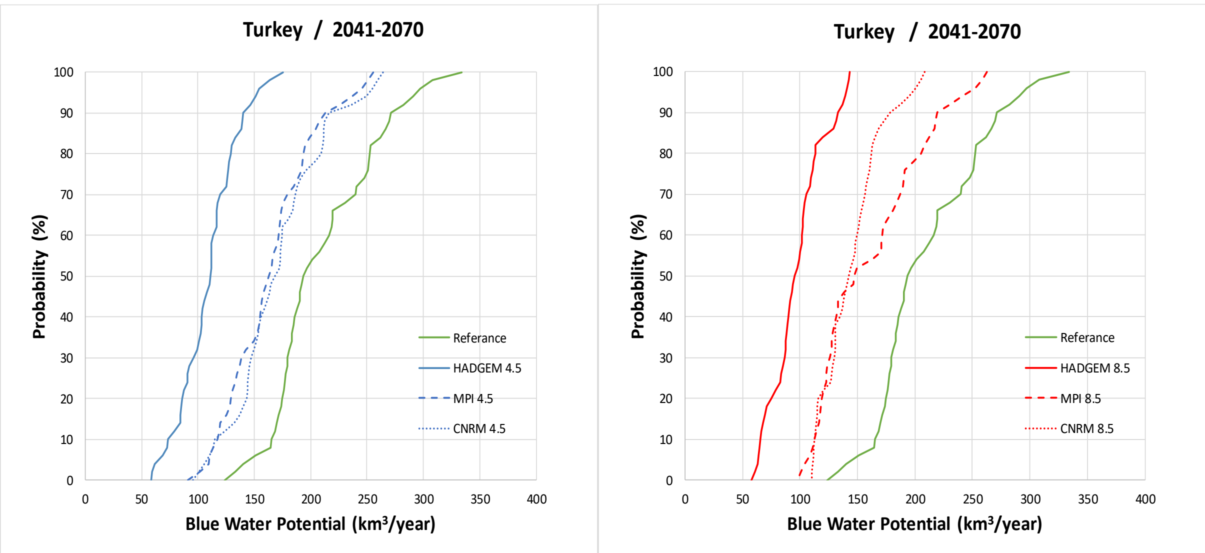
The water potential is distributed among four main water-demanding sectors (water intended for human domestic need, industry water, agricultural/irrigation water, and environmental flow). Along with the population estimations, municipal, industrial and agricultural activities specifically distinct to each watershed have been taken into consideration. The drinking and utility water (domestic/municipal water) water component takes up 23% of the total water requirement in Turkiye. Equivalent net water consumption of within the range of 100-200 L/capita-day is taken with respect to the social and economic structure of population in the basins. Watershed-based urban and rural population projections were finalized through comparison of estimates made in various national and international data sources for Turkiye. Assuming the overall water transmission network (water pipelines and distribution equipment's appurtenances) will be mostly be leak-proof over time, the decrease in water requirement due to eliminated losses has also been considered in the calculations. Agricultural water component equals to almost 70% of the total current water consumption in Turkiye. It was accepted that agricultural (mainly irrigation) water requirement will change as all areas that can be irrigated will gradually be provided with irrigation water by 2030. On the other hand, new methods and technologies, such as transition from the conventional irrigation systems to modern irrigation techniques that require less and efficient water use to provide for the same level of crop yield, and the selection of locally and environmentally suitable crop pattern is considered to be fully established by 2030. Although the water requirement of the industrial sector varies significantly among watersheds, the total of industrial water constitutes only 7% of the total water demand of the country. It should also be noted that the technically and economically unavailable water should be sufficient for the environmental flow requirements. DSI requires at least 10% of natural flow to be enabled at water structures.

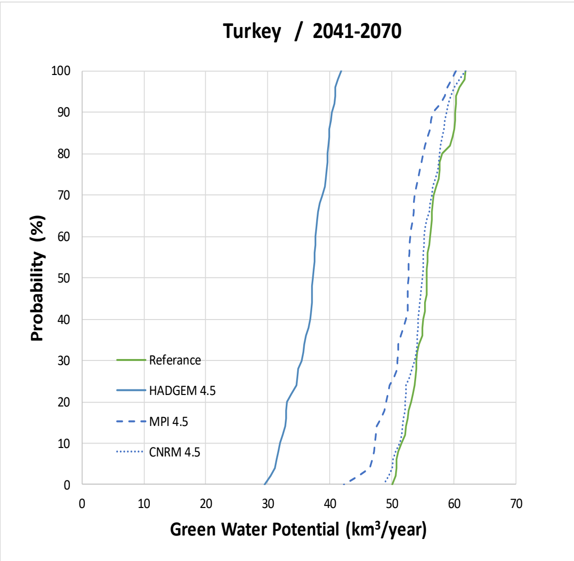
The highest water deficit throughout the century was observed in the results of both scenarios of the HadGEM2-ES model, while the other two models produced generally similar results for both scenarios with certain exceptions. In particular, it can be stated that the water deficit may become even more pronounced regarding all models and scenarios from 2050s onwards.

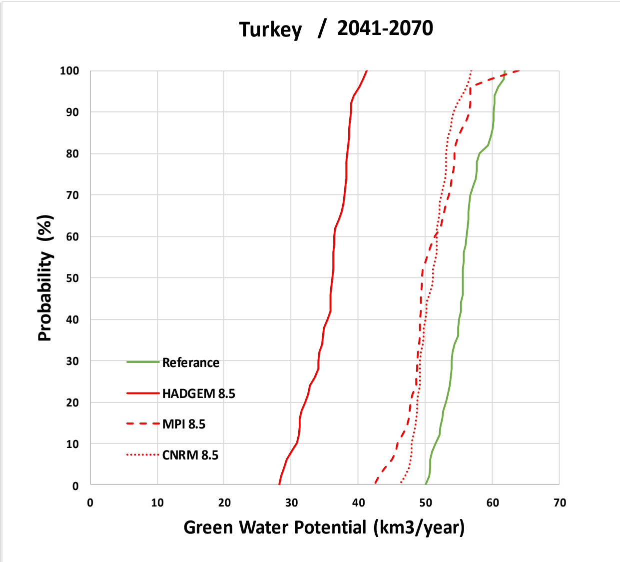
The water budget components estimated through hydrological modelling for 3 different global climate models and 2 emission scenarios (RCP4.5 & RCP8.5) were compared with the DSI data for the reference period within the scope of the study. Total water yield (blue water yield or surface water potential), along with groundwater supply (deep aquifer recharge), as being the most important components of water budget, showed a limited deviation (± 2.3%) relative to the reference period values according to SWAT model estimates (Table 2). The hydrological model also revealed that the relative deviation for all of the 25 watersheds of Turkiye, obtained through the same way with respect to DSI data, range from a minimum of 0.24% to a maximum of 8.90%, confirming the condition that all should be within the <10% range. Thus, it is shown that the hydrological model projections are to be safely used for both the watershed-scale and the country-scale.

In the next stage of the hydrological modelling study, the calibrated hydrological model has been re-run for the 2015-2100 period with the meteorological time series derived from the outputs of global climate models in order to finalize the hydrological projections. Projections of blue and green water obtained for 2 scenarios (RCP4.5 and RCP8.5) and for 3 different climatic climate models were analyzed in 3 consecutive (~30 year) intervals for the century. For all intervals, each model output has been accepted as an independent statistical sample belonging to the same population, and median (X0.50: 50th percentile) and 90th percentile (X0.90) values were determined by means of cumulative probability distributions (S-curves).

Figure 3 presents the blue and green water potential trends (S-curves) of Turkiye with respect to 3 models x 2 scenarios respectively for the 2nd projection period of 2041-2070 selected as the main example. While the same efforts were also given to the other projection periods, further statistical analyses have been conducted with the basic aim of validating the model outputs in the medium term, and for comparing the projected water potentials with regards to the reference values. During the 2041-2070 period where the effects of climate change in the watershed were expected to emerge clearly, the decreases in the median blue water yield with respect to the median values of the reference period are were calculated as (-)43%, (-)16%, (-)13% for the relatively optimistic (RCP4.5) scenario, and as (-)51%, (-)24%, (-)27% for the pessimistic scenario (RCP8.5), respectively for HadGEM2-ES, MPI-ESM-MR, and CNRM-CM5.1 models.







(a) **(b)**

Fig. 3: Blue and green water potential S-curves of Turkiye in 2041-2070 period for climate change scenarios of **(a)** RCP4.5, **(b)** RCP8.5

4 Conclusions

In this study, the impacts of global climate change on the blue and green water potentials of Turkiye were investigated. The hydrological modelling has been conducted for the first time in terms of the whole country-scale, where the hydrological model of SWAT has been configured based on all 25 watersheds and a total of 2480 sub-basins of Turkiye, calibrated through river flows (water yields) and deep aquifer recharges for the reference period of 1971-2000. The hydrological modelling outcomes indicated that the global climate change impacts on Turkiye's blue and green water potential will be significantly apparent especially after year 2040 (2041-2100 period).

The possible negative impacts of global climate change on blue and green water potentials of Turkiye indicate that the water demand projections of water-related sectors -particularly agriculture- needs to be reconsidered and revised further. In this context, pro-active measures that include modern irrigation methods to be expanded, measurement and pricing of irrigation water to be made accurately and accordingly, regulation of crop pattern with respect to water supply ("agriculture according to water") should be utilized for reducing the agricultural water demand, especially where critical. In watersheds that will be subjected to relatively high impacts of global climate change, it is required that sectoral water allocation planning to be made for effective and efficient management of water resources under the light of increasing climate change resilience with emphasis on water recovery and reuse. The expected 30% reduction in river flows requires the development of some water resources that are currently regarded as technically and economically unavailable (non-feasible for retrieval). The reduction of 40% in aquifer recharges reveals the need to manage underground water reserves while maintaining the sustainability of natural recharges and water balance. Similarly, the expected ~15% reduction in soil humidity (green water) may negatively affect the dry (precipitation-fed) agricultural activities along with and natural vegetation.

Such hydrological modelling studies and simulations of various scenarios may lead to further evaluations that may help the scientists working in the field of climate change and hydrology.

Projections and the outcomes derived from these studies particularly take the attention of various disciplines, such as meteorologists and environmental engineers as well as the policy-makers at both local, regional, and national levels dealing with different levels of climate change adaptation policies.

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