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Research article

Comprehensive assessment of irrigation water requirements in Iran

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Abstract: A national web-based simulation portal was developed to estimate the irrigation water requirements at plain scale in Iran. The National Water Portal (NWP) consists of four national databases (climatic, soil, crop, and spatial data), a lumped water balance model, and a graphical user interface (GUI). The irrigation water requirements in standard conditions were estimated based on the dual crop coefficient approach presented by FAO 56. Net irrigation requirements (NIR) and gross irrigation requirements (GIR) were calculated for 125 different crops cultivated in the 609 plains in Iran. Results were aggregated at both political and hydrological scales. The statistical comparison between the estimated NIR and reported values in the literature reviews indicates a correlation coefficient of 75% with root mean square error (RMSE) of less than 280 m^3 ha^{-1}. Results showed that sugar cane has the highest NIR value (18318 m^3 ha^{-1}) among the studied crops, and sugar beet has the second highest NIR value (5100–11896 m^3 ha^{-1}). The aggregated amount of NIR and GIR for the entire country was calculated as 47 and 105 billion cubic meters (BCM), respectively. Results indicate that 3.772 million cubic meter (MCM) of water can be saved by applying 15% water stress. By increasing the irrigation efficiency to 65% without considering any water stress, 3.482 MCM of water can be saved.

Keywords: water consumption; crop evapotranspiration; net irrigation requirement; soil water balance; water management

1. Introduction

During the last 50 years, Iran has faced numerous severe and prolonged droughts, which have significantly threatened water availability in agricultural sector and created economic and social difficulties [1]. The outlooks of long-term climatic forecasts indicate that water shortage in most areas of the country will continue and show that Iran is moving towards water crisis in the future [2,3]. Furthermore, due to the massive gap between the demand and sustainable supply of water, Iran is experiencing widespread water shortage and unprecedented challenges in securing water and food [2] for its growing population, which is projected to reach 92 million by 2050 [4].

Although a significant part of the water scarcity in Iran is attributed to the country's natural climate and impacts of climate change, the mismanagement and government policies over the past few decades have intensified the trend of water scarcity in Iran. The total renewable water resources in Iran have been reported as 106 ± 17% billion cubic meters (BCM) which share of its groundwater is 37 ± 6% BCM [5]. However, the reports indicate total groundwater depletion in Iran is beyond the allowed limits announced by water authorities in Iran [6]. Although less than 6% of the total land area is under irrigated cultivation, the agricultural water requirement accounts for 92% of the total water demands, while the shares of municipal and industrial sectors are 6% and 2%, respectively.

Resolving the water challenges and moving toward the sustainable condition requires a thorough reconsideration of how much water is consumed, especially in the agricultural sector, and making balance between the water demands and renewable water resources under the climate change conditions. Estimation of the water consumption in the agriculture sector and amount of water requirements under climate change impacts are the key elements in the macroplanning related to the supply, allocation and principal of water management [7]. However, the water consumption in agriculture is yet to be determined accurately, and this issue has always been one of the main concerns of water authorities in Iran.

Computation of water consumption in irrigated areas is typically achievable using the simulation of water balance components on a daily basis. The simulation of water balance components is often performed through comprehensive agro-hydrological modeling (CropSyst, HYDRUS, SWAP, SWAT, and AquaCrop) at a farm scale. These models are often too complex in terms of required data, and are not recommended to be applied widely in practice. In contrast to agro-hydrological models, lumped soil water balance-based models (FAO, BUDGET, OSIRI, PILOTE and SIMDualKc) require less soil in-put data with easier crop parameterization, and may employ a simpler procedure for estimating water consumption.

Therefore, the purpose of this study was to develop a national web-based simulation tool in order to estimate the potential water consumption on a national scale. This paper introduces a National Water Portal (NWP) consisting of national climatic, soil and crop databases, simulation model and graphical user interface (GUI) to estimate total water consumption in agriculture on a national scale. The NWP is based on daily water balance and adheres closely to the FAO-56 methodology and can serve as a convenient and effective means to compare net irrigation water requirement (NIR) in different plains and climate conditions.

2. Materials and methods

2.1. Study area

Iran occupies a region of around 1.648 million km^2 (Figure 1a). The total land area of Iran is divided into six main basins which consists of 30 sub-basins (Figure 1b). Each sub-basin is divided into subsequent micro-watersheds/catchments which are called "plains" in this study (Figure 1c). With heights ranging from 25 meters to 5600 meters, the country's diverse geographic areas have produced a wide diversity of climates (Figure 1d). Average annual precipitation for the entire country is roughly 257 mm (370 km^3), whereas precipitation can range from as low as 50 mm/year in deserts up to more than 1500 mm/year in the coastal regions of the Caspian Sea and the northern side of the Alborz Mountain range. The total annual precipitation equals 412 BCM (Figure 1b). Most of the rainfall in this country takes place in fall and winter, which is the period of minimum water requirements for crops. In summer, when the water consumption of plants is at its peak, the climate of Iran lacks effective rainfall [6].

2.2. Modeling approach

The NWP model consists of three distinctive components: a database, a mathematical model, and a graphic user interface. The database stores and retrieves information on climate, soil hydraulic properties, crop characteristics, irrigation systems, and general data representing the soil profiles and synoptic stations for each plain. The structure of the NWP provides easy connection to different types of databases, including climate, soil, crop, and spatial, and enables the estimation of crop water requirement (CWR) and NIR from the farm level to regional level. The graphical user interface (GUI) is the actual frontend of the developed platform and provides easy use by farmers. The structure is designed to be interfaced via the Web to support decision-making in regards with irrigation requirements.

In this model, each plain is considered as a broad farm, and standard irrigation scheduling based on FAO-56 guidelines is implemented to calculate NIR. Synoptic data (including maximum and minimum air temperature, relative humidity, wind speed, sunshine hours, and precipitation) and soil profile data (including total available water, readily available water, and management allowed depletion in upper and lower layers) as well as plant characteristics (125 different crops) and their cultivation area were used as input data into the model. Considering the genetic variety of cultivated crops in each plain, the data used in the modeling belonged to the dominant type. Since the surface irrigation method is still the dominant type of irrigation in Iranian farms and end of each plot is closed by this irrigation, the surface runoff was not considered.

A detailed scheme of the NWP structure is presented in Figure 2. It indicates a schematic view of main components such as database, relations, and available results. The following sections provide a description of a standardized formulation of CWR and NIR computation as implemented in the NWP portal. The methodologies have been compiled from guideline provided by FAO-56.

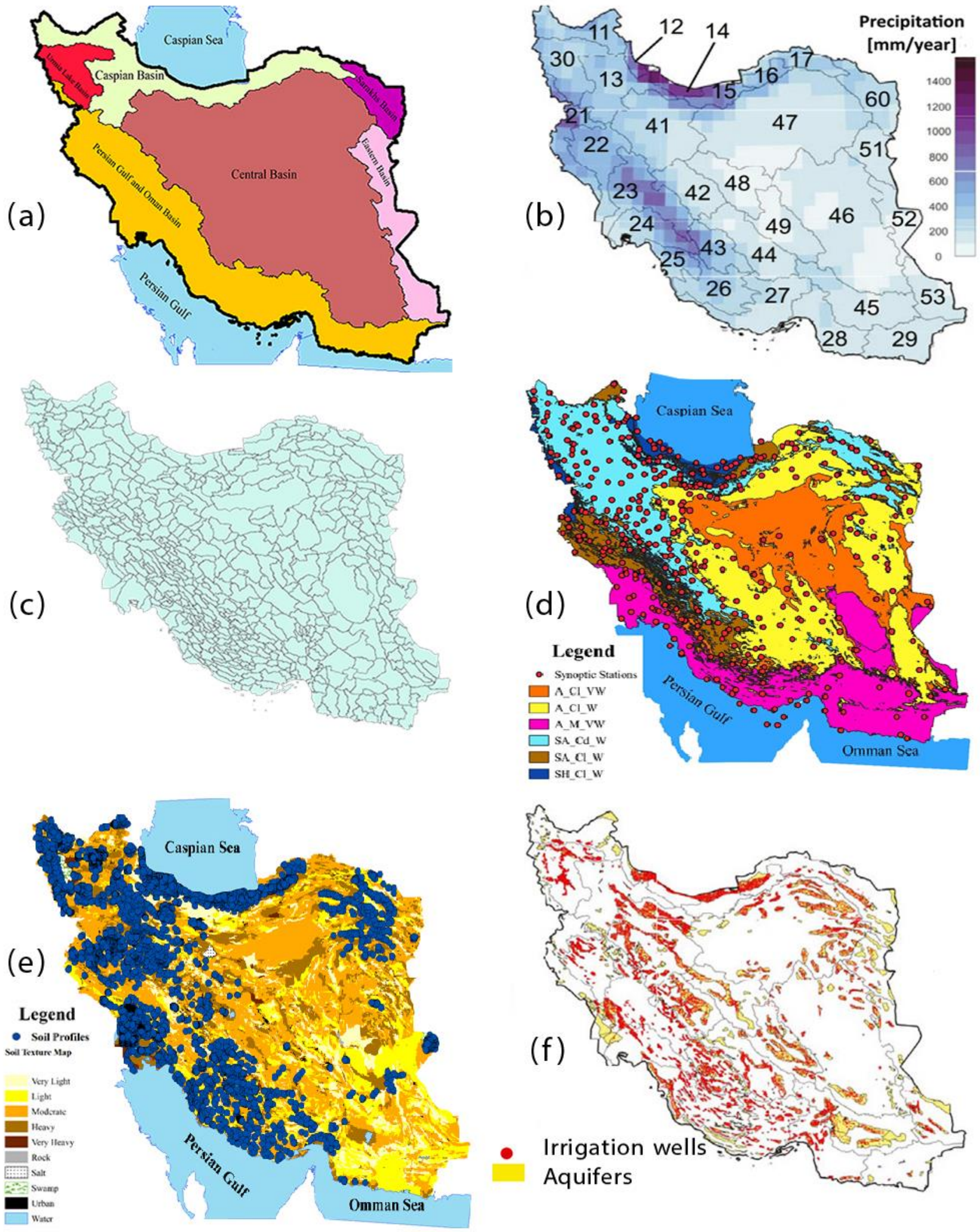

Figure 1. Description of spatial data implemented in the calculation process of irrigated water requirements (a) Main basins (b) Sub-basin divisions along with long-term average (1980–2016) annual precipitation spatial distribution (c) Micro catchments (plains), (d) Agro-climatic zones based on [8] classification system with location of the meteorological stations, (e) Map of Iran soil texture classes with location of soil profiles (SWRI, 2018), and (f) Spatial distribution of irrigation wells and the aquifers in Iran (Ministry of Energy, Iran).

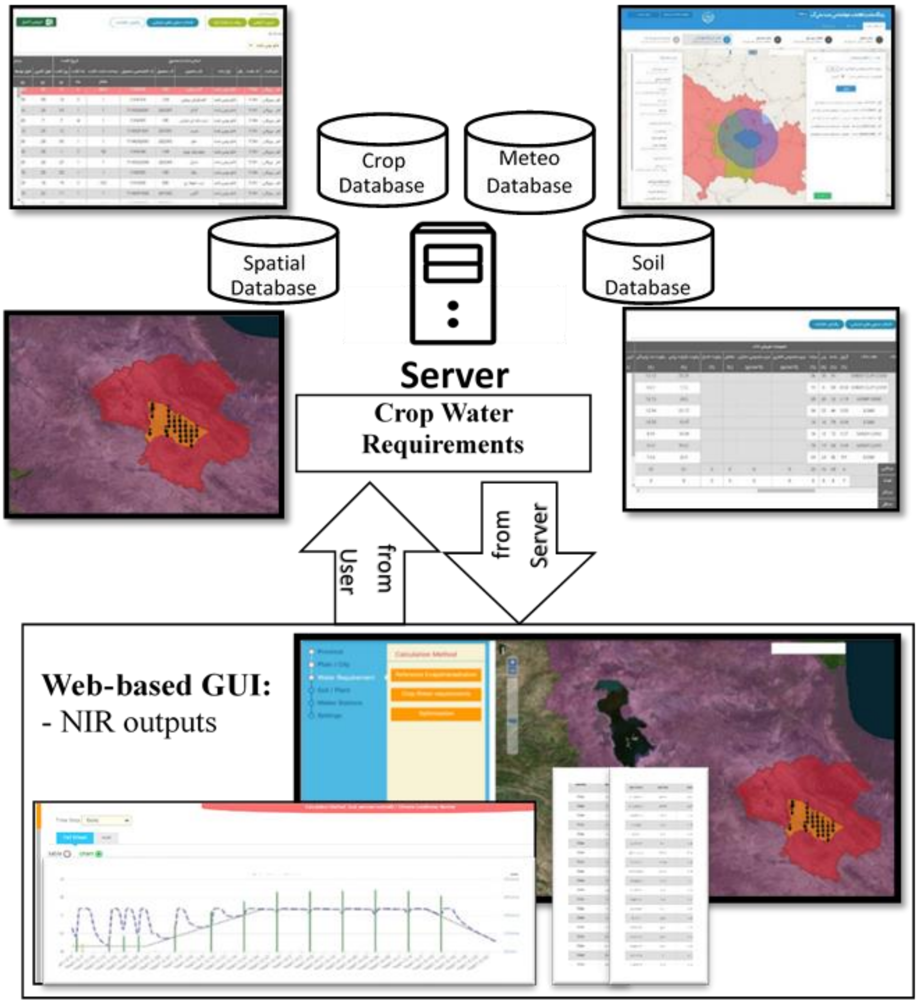

Figure 2. The flowchart of a national web-based DSS system.

2.2.1. Soil water balance

The soil water balance (i.e., the depletion in the root zone) is calculated at the end of each day using a two-layer lumped model as [9,10]:

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{C,i} + Dpi \quad (1)$$

where $D_{(r,i)}$ is the root zone depletion at the end of day i (mm), $D_{(r,i-1)}$ is the root zone depletion at the end of the previous day (i – 1) (mm), P_i is the precipitation on day i (mm), RO_i is the runoff from the soil surface on day i (mm), I_i is the net irrigation depth on day i that infiltrates the soil (mm), CR_i is the capillary rise from the groundwater table on day i (mm), $ET_{(C,i)}$ is the crop evapotranspiration on day i (mm), and DP_i is the water flowing out from the root zone depth.

The soil water balance in the root zone is estimated assuming the soil profile is divided into two layers: the upper layer with a 15 cm thickness where evaporation takes place and the underlying layer that develops from the bottom of the upper layer to the root depth. The underlying layer behaves like a reservoir and its thickness increases as much as roots grow.

2.2.2. Crop evapotranspiration

NWP estimates crop evapotranspiration (ET_c) using a crop coefficient (K_c) multiplied by the reference evapotranspiration (ET_0) [9]. The NWP model implements the dual crop coefficient approach to determine the effects of soil evaporation and crop transpiration separately. The approach for the calculation of ET_c is implemented as:

$$\mathrm{ET_c} = \mathrm{K_c} \times \mathrm{ET_0} \tag{2}$$

$$\mathrm{K_c} = \mathrm{K_e} + \mathrm{K_{cb}} \tag{3}$$

where K_{cb} is the basal crop coefficient and K_e is the evaporative coefficient. Basal crop coefficient (K_{cb}) describes primarily the crop transpiration component, and direct evaporation from the soil surface is described by the soil evaporation coefficient (K_e). ET_0 is the reference evapotranspiration. In NWP, ET_0 can be estimated using several empirical to semi-empirical models based on meteorological data availability such as radiation-based model [11], temperature-based model [12], and combination-based model [9].

2.2.3. The basal crop coefficient (K_{cb})

To draw the basal crop coefficient (K_{cb}), three values for K_{cb} are required: $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ which represent average values for K_{cb} during the initial, mid, and late periods of growing season, respectively [9,13].

$$\mathrm{K_{cb}}: \begin{cases} \text{if}\{\mathrm{J} < \mathrm{J_{dev}}\} \rightarrow \mathrm{K_{cb}} = \mathrm{K_{cb\ ini}} \\ \text{if}\{\mathrm{J_{dev}} \le \mathrm{J} < \mathrm{J_{mid}}\} \rightarrow \mathrm{K_{cb}} = \mathrm{K_{cb\ ini}} + \frac{(\mathrm{K_{cb\ mid}} - \mathrm{K_{cb\ ini}})(\mathrm{J} - \mathrm{J_{dev}})}{\mathrm{L_{dev}}} \\ \text{if}\{\mathrm{J_{mid}} \le \mathrm{J} < \mathrm{J_{late}}\} \rightarrow \mathrm{K_{cb}} = \mathrm{K_{cb\ mid}} \\ \text{if}\{\mathrm{J_{late}} \le \mathrm{J} < \mathrm{J_{harv}}\} \rightarrow \mathrm{K_{cb}} = \mathrm{K_{cb\ mid}} + \frac{(\mathrm{K_{cb\ end}} - \mathrm{K_{cb\ mid}})(\mathrm{J} - \mathrm{J_{late}})}{\mathrm{L_{late}}} \\ \text{if}\{\mathrm{J} = \mathrm{J_{harv}}\} \rightarrow \mathrm{K_{cb}} = \mathrm{K_{cb\ end}} \end{cases} \tag{4}$$

where J is the day of the year (1–366), J_{dev} is number of day of the year at beginning of development period, J_{mid} is number of day of the year at beginning of midseason period, J_{late} is number of day of the year at beginning of late season period, L_{dev} is length of crop development growth stage (day), and L_{late} is length of late season growth stage (day).

NWP uses the recommended values for K_{cb} for the standard conditions (RH_{min} averaging 45% and with moderate wind speed, averaging 2 (m/s) [9]). The K_{cb} is adjusted for local climatic conditions where non-standard condition is met based on FAO 56.

2.2.4. The soil evaporation coefficient (K_e)

The soil evaporation coefficient (K_e) is maximum when the soil surface is wet, following rain or irrigation and canopy is small. Allen (1998) suggested the procedure for calculation of evaporation in the dual K_c methodology using the following equations [9].

$$\mathrm{K_e} = \min\{\mathrm{K_{cbmax}} \times \mathrm{f_{ew}} \ldots, \ldots \mathrm{K_r} \times (\mathrm{K_{cbmax}} - \mathrm{K_{cb}})\} \tag{5}$$

$$K_r = \max\left\{0\ldots,\ldots\frac{TEW - D_{e,\,i-1}}{TEW - RAW}\right\} \quad (6)$$

$$D_{e,\,i} = D_{e,\,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + T_{ew,\,i} + DP_{e,\,i} \quad (7)$$

$$DP_{e,\,i} = (P_i - RO_i) + \frac{I_i}{f_w} - D_{e,\,i-1} \geq 0 \quad (8)$$

where K_r is the soil evaporation reduction coefficient, TEW (total evaporative water) is the maximum cumulative depth of evaporation (depletion) from the soil surface layer (mm), RAW (readily available water) is the cumulative depth of evaporation (depletion) at the end of stage 1 (mm), $D_{e,\,i-1}$ is the cumulative depth of evaporation (depletion) from the soil surface at the end of the day ($i-1$) (mm), $D_{e,\,i}$ is the cumulative depth of evaporation (depletion) following complete wetting at the end of the day i (mm), P_i is the precipitation on day i (mm), RO_i is the precipitation runoff from the soil surface on day i (mm), I_i is the irrigation depth on day i that infiltrates the soil (mm), E_i is the evaporation on day i ($E_i = K_e{*}ET_0$) (mm), $T_{ew,\,i}$ is the depth of transpiration from the exposed and wetted fraction of the soil surface on day i (mm), $DP_{e,\,i}$ is the deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity (mm), f_w is the fraction of soil surface wetted by irrigation (0.01–1), and f_{ew} is the exposed and wetted soil surface (0.01–1).

2.2.5. Net irrigation requirements

In NWP, irrigation is described in terms of the irrigation scheduling strategy, the irrigation method, and constraints (maximum allowed soil water depletion). The irrigation scheduling strategies consist of standard conditions (no water stress) and assessment of a defined irrigation schedule. Equations for NIR calculation are as follows:

$$ET_{c,\,adj} = (K_s \times K_{cb} + K_e) \times ET_0 \quad (9)$$

$$K_s = \frac{TAW - D_{r,\,i}}{TAW - RAW} \quad (10)$$

$$TAW = 1000 \times (\theta_{FC} - \theta_{pwp}) \times Rd \quad (11)$$

$$RAW = MAD \times TAW \quad (12)$$

$$NIR_i = ET_{c,adj,i} + DP_i + RO - P_i + D_{r,\,i} \quad (13)$$

where Ks is the water stress coefficient, TAW is the total available soil water in the root zone (mm), θ_{FC} is the water content at field capacity, θ_{pwp} is the water content at permanent wilting point, Rd is the depth of the root zone, MAD (management allowed depletion) is the average fraction of TAW that can be depleted from the root zone before moisture stress occurs (0–1), DP_i is the water loss out of the root zone by deep percolation on day i (mm), $ET_{c,\,adj\,I}$ is the adjusted crop evapotranspiration on day i (mm), NIR_i is the net irrigation requirement on day i (mm), RO_i is the surface runoff on day i (mm), and P_i is the precipitation on day i (mm).

In this study, the irrigation scheduling strategy was set on standard conditions and irrigation was applied as soon as a proportion of TAW was depleted. The irrigation depth was determined based on the difference between the amount of water depleted and field capacity (θ_{FC}). The initial soil moisture was set on residual soil moisture of θ_{pwp} to force the model to apply an irrigation because farmers start with heavy irrigation after a period of dryness.

The time step where the calculations are conducted is a crucial factor in solving the water balance equation. Commonly, the equation is considered for monthly steps. However, in this study, the soil water balance equation was discussed on a daily basis in order to predict the irrigation events. In the end, cumulative NIR should be compatible with the following equation:

$$\sum \mathrm{NIR} + \sum \mathrm{P} = \sum \mathrm{RO} + \sum \mathrm{DP} + \sum \mathrm{ET_c} + \Delta\theta \quad (14)$$

where $\sum NIR$ is the cumulative irrigation depth during a growing season, $\sum P$ is the cumulative precipitation, $\sum RO$ is the cumulative runoff, $\sum DP$ is the cumulative deep percolation, $\sum ET_c$ is the crop evapotranspiration from the dual crop coefficient approach, and $\Delta\theta$ is the soil moisture difference of the end and beginning of a growing season (mm).

The accuracy of dual crop coefficient approach has been confirmed by several studies during last decade [14–16].

2.2.6. Gross irrigation requirements

The total amount of water, inclusive of losses, applied through irrigation is termed as gross irrigation requirement (GIR). The NIR divided by the irrigation efficiency gives IR. The efficiency for each plain was acquired from official reports [5]. Also, a few efficiency scenarios were assessed as explained in 2.3.4 and 3.5.

2.3. Datasets

Four major databases were used in this study: (1) climatic data, (2) soil data, (3) crop data, and (4) irrigation efficiency. Detailed descriptions of these databases are presented in the following subsections.

2.3.1. Climate database

Long-term daily climate data including maximum and minimum air temperature, relative humidity, wind speed, sunshine hours, and precipitation for the period of 1980–2017 were obtained from 407 synoptic stations and 560 climatological stations, which respectively belong to the Iran Meteorological Organization and Ministry of Energy. The data was transferred to the web-based weather database with capability of producing 5–30 years-average of climate data and presenting time-series of each parameter.

Since crop phenology and irrigation requirements vary with climate, an agro-climatic zones map of Iran was employed in the calculation of irrigation requirements in the NWP portal. This map has been produced using the UNESCO classification system, which is based on humidity, winter and summer type for arid zones.

The agro-climatic zones map was categorized into six major climatic zones including arid with cool winter and very warm summer (A_Cl_VW), arid with cool winter and warm summer (A_Cl_W), arid with mild winter and very warm summer (A_M_VW), semi-arid with cold winter and warm summer (SA_Cd_W), semi-arid with cool winter and warm summer (SA_Cl_W), and semi-humid with cool winter and warm summer, SH_Cl_W (Fig.2). The SH_Cl_W climate was the smallest area, whereas arid regions (A_Cl_VW, A_Cl_W, and A_M_VW) were the predominant climate in the country.

2.3.2. Soil database

More than 32000 soil profiles containing general information (reports, coordinates, and exclusive codes), physical properties (texture, structure, bulk density, and water-holding capacity and infiltration rate) and chemical properties (pH, salinity, and organic matter) were collected from different sources produced by both government and private section over the past 25 years. In addition, a national-scale general soil texture map generated by Soil and Water Research Institute (SWRI 2018) was implemented in the calculation of irrigation requirements. This map has been produced by overlaying several maps including Iran's Land Suitability for Agriculture map [4] and Iran land use/land cover map.

The map consisting of 10 soil types was reclassified into 5 texture class including very light, light, moderate, heavy, and very heavy, for simplification (Table 1).

Table 1. soil texture classes of Iran (SWRI, 2018).

No.	Texture class	Texture type
1	Sand	Very light
2	Loamy sand	Light
3	Sandy loam	Light
4	Loam	Moderate
5	Silt loam	Moderate
6	Silt	Moderate
7	Sandy clay loam	Heavy
8	Silty clay loam	Heavy
9	Clay loam	Heavy
10	Sandy clay	Very heavy
11	Silty clay	Very heavy
12	Clay	Very heavy

2.3.3. Crop database

General data on crop parameters and irrigation management was derived from different national and international sources including FAO, Ministry of Agriculture, reports of agriculture research institutes, comprehensive studies on agriculture management in Iran, and Statistical Center of Iran. These data were later localized by vast field surveys among both farmer communities and agricultural experts in each province. The field surveys for the major crops in the 609 plains of Iran were conducted by a joint cooperation between APERDRI (Agricultural Planning, Economic and Rural Development Research Institute) and Agriculture and Horticulture department of Ministry of Agriculture, during the 2016–2017 growing season (Table 2). Nasiri (2014) provided the data on growth length of major crops which was validated by time series of vegetation indices derived from Landsat and Sentinels images [19].

Table 2. Crop input parameters implemented in performing FAO dual Kc approach.

Parameter	Definition	Source
Planting date	Planting month and day	APERDRI + Field surveys
Length of growing stages	Length of initial stage, development stage, middle stage and late-season stage	APERDRI + Field surveys
Basal crop coefficients	Initial basal crop coefficient, Middle basal crop coefficient and Late-season basal crop coefficient	Table 17, FAO.56
Crop height	Maximum crop height (m)	Ministry of agriculture + Field surveys
Root depth	Minimum and maximum rooting depth (m)	Ministry of agriculture
Management allowed depletion	Management allowed depletion at the initial stage (%) and during the growing season (%)	Table 22, FAO.56
Evaporative soil depth	The soil depth affected by evaporation (mm)	0.1–0.15
Yield	Crop yield	APERDRI
Slope Yield Coefficient	Slop coefficient of yield reduction	FAO.56
Sensitivity Coefficient	Crop sensitivity coefficient	FAO.56
Economic data	Rent, planting, mechanization harvest and sell	APERDRI
Irrigation method	Type of irrigation used for each field	Ministry of agriculture + field surveys
Fraction of wetted soil surface	The fraction of soil surface wetted by precipitation or irrigation	The type of the irrigation system and table 20 of FAO.56

The analysis of the irrigation efficiency measured from 1900 irrigated fields administered by farmers across the country in the period of 1991–2015 [5] were used to calculate GIR from estimated NIR. Apart from that, three different scenarios including 56% (the average efficiency of irrigation systems in Iran according to [17]), 65% (a reliable and accessible irrigation efficiency), and 100% was implemented to evaluate different possibilities of water management and compare the current situation with ideal circumstances. Also, a rate of 15 % (the highest amount of stress that farmers usually exert on crops) water stress was applied to the net irrigation water requirements calculated by NWP portal to convert the net irrigation water in standard conditions to the actual data.

3. Results

3.1. Statistical data

The statistical data for the main crops was classified and reported on the basis of agro-climatic zones (Table 3). Wheat, barley, sugar beet, and forage maize are planted in all the agro-climatic zones as major cultivated crops across the country as indicated in the Table 3. The absence of rice in the SA_Cd_W climate can be observed, and sugar cane is solely cultivated in the A_M_VW climate (southwest of Iran). The studied crops are mainly planted in the regions with A_Cl_W and A_Cl_VW climates. Among the cultivated crops, winter wheat comprises of more than 50% of the cultivated areas and 68% of paddy fields located in the SH_Cl_W climate. Sugarcane is only cultivated in the A_M_VW climate.

Table 3. The cultivated area of each crop under different climatic conditions.

Crop type	Area	Climate						Total area
		A_Cl_W	SH_Cl_W	A_Cl_VW	SA_Cd_W	SA_Cl_W	A_M_VW	
Winter	ha	596685	29147	567851	34148	548941	351565	2128340
wheat	%	28.0	1.4	26.7	1.6	25.8	16.5	52.47
Winter	ha	264602	2803	320364	20558	86861	40411	735601
barley	%	36.0	0.4	43.6	2.8	11.8	5.5	18.13
Rice	ha	12743	407831	10868	-	114997	49251	595693
	%	2.1	68.5	1.8	-	19.3	8.3	14.68
Maize	ha	19655	629	55816	-	68346	25690	170138
	%	11.6	0.4	32.8	-	40.2	15.1	4.19
Sugar	ha	61055	24.4	20722	2151	25983	835	110772
beet	%	55.1	0.0	18.7	1.9	23.5	0.8	2.73
Forage	ha	58987	2193	89666	454	56924	15087	223314
maize	%	26.4	1.0	40.2	0.2	25.5	6.8	5.50
Sugar	ha	-	-	-	-	-	89565	89565
cane	%	-	-	-	-	-	100.0	2.21

3.2. The duration of the growing season and reference evapotranspiration

Data on crop growing duration obtained from filed surveys and cumulated ET_0 over the growing seasons of the studied crops were laid out in Table 4. The duration of the growing season is profoundly influenced by the planting dates, crop varieties, and climatic elements. The shortest and longest time usually occurs in the A_M_VW climate and the SA_Cd_W climate, respectively. Mokhtari et al. (2019) analyzed the duration of the growing seasons of major crops in three different agro-climate zones (SA_Cd_W, A_Cl_W, and A_M_VW) of Iran using satellite data and concluded similar results [18]. The warmer temperature in both A_Cl_W and A_Cl_VW climates causes the time of the growing seasons to be shorter. Also, the warmth and humidity in the SH_Cl_W and SA_Cl_W climates along with using early season crops leads to even shorter growing period in these areas.

Table 4. The lengths of the growing seasons and the cumulative referenced evapotranspiration (ETo) within entire growing season under different climatic conditions.

Crop type	Crop growth length (Day)/Cumulative ET_0 (mm. season-1)											
	A_Cl_W		SH_Cl_W		A_Cl_VW		SA_Cd_W		SA_Cl_W		A_M_VW	
Winter wheat	250/	674	167/	222	198/	647	265/	512	227/	636	167/	636
Winter barley	240/	574	152/	192	183/	507	250/	413	212/	531	152/	468
Rice	101/	602	97/	429	91/	660	-	-	111/	707	95/	737
Maize	142/	820	138/	608	123/	737	145/	593	138/	899	117/	618
Spring sugar beet	212/	1038	195/	701	181/	1156	215/	864	202/	1148	180/	1229
Forage maize	122/	736	118/	569	103/	681	124/	590	118/	802	96/	541
Sugar cane	-		-		-	-	-	-	-	-	405/	1976

ET_0 is the quantitative form of the climatic condition [9]. The cumulative ET_0 in the areas with SA_Cd_W and SH_Cl_W climates was the lowest because of the low air temperature in the SA_Cd_W climate and the high humidity with a relatively low temperature in the SH_Cl_W region, Whereas ET_0 in the A_M_VW and A_Cl_VW climates was relatively high. In general, ET_0 is affected by the duration of the growing period. With the increasing of the length of growing season, the cumulative ET_0 will increase.

3.3. Irrigation water requirements

Figure 3 depicts the cumulative GIR and NIR of an agricultural year in each plain obtained from NWP in million cubic meters (MCM). As is shown, deserts and mountain areas in the Zagros and Alborz mountains, which have very little or no cultivated areas, have the lowest GIR and NIR ranging from 0 to just under 80 MCM. Maximum NIR was seen in southwestern areas with dominant cultivation of sugar cane, parts of northern plains with dominant cultivation of rice, and parts of southern plains which face a high temperature and dry conditions (A-M-VW) and with a vast cultivation area. Furthermore, areas with the lowest irrigation efficiency, such as Qazvin, Alborz, and Tehran, have the maximum amount of GIR. Overall, visual observation indicates a high compatibility of the results with topographic and climatic maps and the model has been able to provide a good estimate of the spatial distribution of NIR and GIR for each plain.

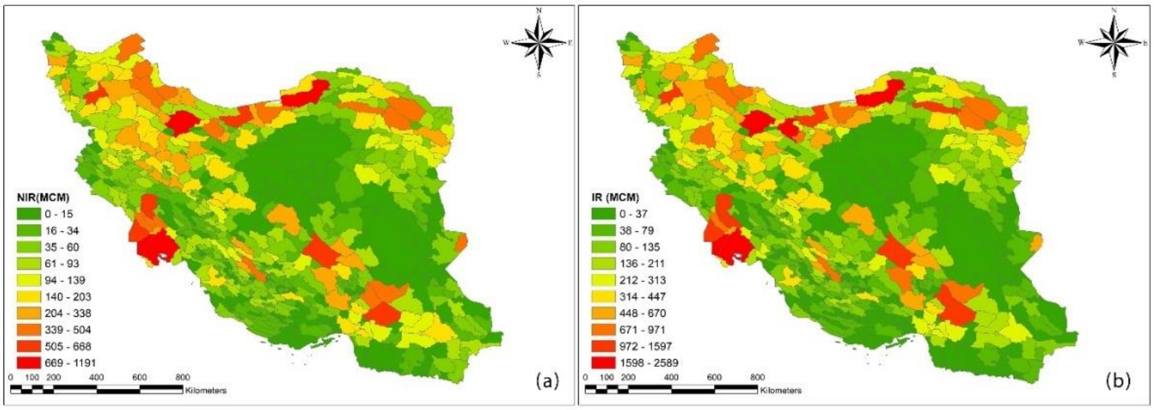

Figure 3. Spatial distribution of cumulative net irrigation requirements (NIR) and gross irrigation requirements (GIR) estimated by the NWP (MCM).

Sugar cane with ET_c of 1976 mm has the highest ET_c among the studied crops because of its long period of growing season. Sugar beet with ET_c of 636–1208 mm has the highest water consumption after sugarcane. ET_c of rice varies from 489 to 916 mm and its ET_c in the SH_Cl_W climate is lower than other agro-climate zones. ET_c of maize and forage maize varies from 440 to 702 mm which is lower than ET_c for sugarcane, sugar beet, and rice. Winter wheat and barley with ET_c of 168–555 mm has the lowest ET_c among the studied crops.

NIR directly follows the changes in ET_c (Eq.6 and Eq.22). Therefore, the variations of NIR in different parts of Iran is a function of variation of ET_c. Sugar cane with NIR of 18318 $m^3\ ha^{-1}$ has distinguishably higher NIR value among the studied crops because of its long growing season. Sugar beet with NIR of 5100–11896 $m^3\ ha^{-1}$ stands in the second place in terms of required water, and rice with NIR of 4495–8907 m^3 ha^{-1} has the highest NIR after sugarcane and sugar beet in all the agro-climatic zones. NIR for maize and forage maize (3747 to 7083 m^3 ha^{-1}) is lower than NIR for sugarcane, sugar beet, and rice. Winter wheat and barley with NIR of 258–4235 m^3 ha^{-1} has the lowest NIR among the studied crops.

The highest NIR is for Qazvin plain with 1.191 MCM and the lowest belongs to scattered plains around the central basin. However, the highest GIR for Tehran-Karaj plain is 2.589 MCM. This is a high amount of water demand considering the cultivation area of the plain which is caused by the dense cropping pattern and the low efficiency in this strategic plain that is mostly under cultivation of wheat, maize, and barley.

In Figure 4, the average NIR for major crops (wheat, barley, rice, maize, sugar beet, forage maize, and sugar cane) is displayed based on climatic classification. As can be seen, the amount of water demand shows a high correlation with the climatic conditions of different regions.

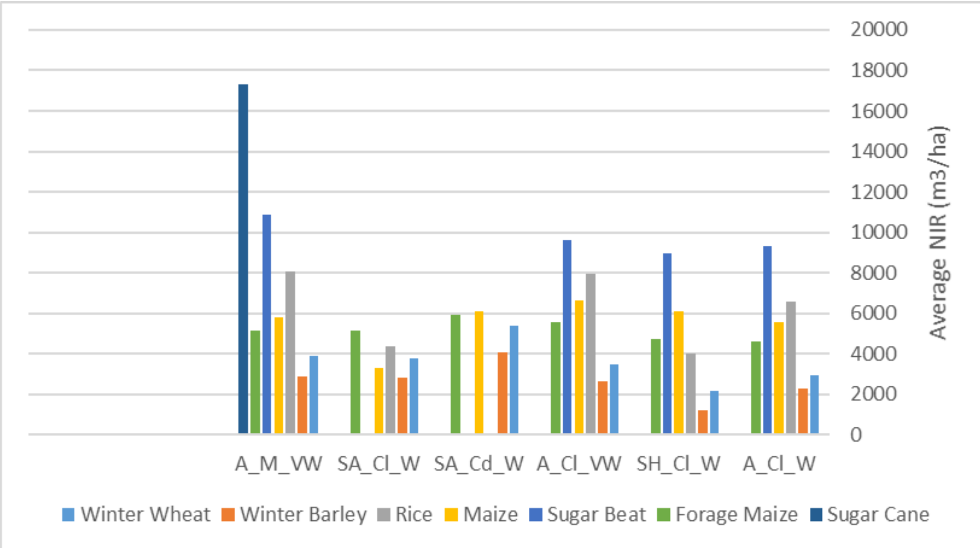

Figure 4. Average net irrigation requirements (NIR) of main crops in different climate categories.

In Table 5, the aggregated NIR and IR for sub-basins and main basins are presented in MCM. The lowest obtained NIR belongs to Eastern basin and Mashkel sub-basin with 1298 MCM and 298 MCM, respectively. The highest amounts belong to the Central basin and Namak lake sub-basin with 44781 MCM and 5472 MCM, respectively. Total amount of NIR and GIR for the entire country are estimated to be around 47 BCM and 105 BCM, which are consistent with the results obtained from the official reports of the Ministry of Energy [5].

3.4. Assessment and evaluation

Due to the existence of various climatic conditions, cultivated crops, altering physical and chemical properties of soils across the country, and in the absence of an integrated network of lysimetric data in Iran, a comprehensive accuracy assessment of NWP outputs with the references data was not possible. Instead, an attempt was made to assess the accuracy of results by comparing the estimated total gross irrigation requirements (GIR) with the amount of water withdrawal by agricultural tube-wells in each plain (Figure 5). Since groundwater resources has a very high share in the supply of needed water by agricultural sector in Iran and more than 91% of water in the basins is consumed by this sector, comparison of total GIR and the amount of water withdrawals by agricultural tube-wells can be an effective approach in evaluating the accuracy of developed system.

Table 5. Cumulative estimated net irrigation requirements (NIR) and gross irrigation requirements (GIR) for main basins and sub-basins of Iran in agriculture year.

Main Basin	Sub-basin	CODE	NIR(MCM)	GIR(MCM)
Caspian Basin	Aras	11	1770	3338
	Talesh rivers	12	506	1007
	Sefi rud	13	2187	4948
	Sefid rud - Haraz	14	377	759
	Qarah Su - Haraz	15	1396	2918
	Qarah Su - Haraz	16	861	1925
	Atrak	17	659	1489
	Total	7756	16384	
Persian Gulf and Oman Basin	Western border	21	1025	2214
	Karkheh	22	3187	6990
	Karun	23	4394	10539
	Jarahi - Zohreh rivers	24	1767	4024
	Helleh	25	576	1141
	Mand	26	1350	2552
	Kol - Mehran rivers	27	972	1952
	Bandarabbas - Sadich	28	1167	2460
	South Balochistan	29	408	610
	Total	14846	32482	
Urmia Lake Basin	Urmia lake	30	2958	6051
	Total	2958	6051	
Central Basin	Namak lake	41	5472	14641
	Gavkhouni	42	1109	2653
	Tashk - Bakhtegan - Maharlu	43	2064	3850
	Abarkuh - Sirjan	44	1188	2476
	Hamun e Jaz Murian	45	2145	4295
	Dasht e Lut	46	1316	2856
	Dasht e Kavir	47	3728	9623
	Kavir e Siahkuh	48	451	996
	Darreanjir	49	1569	3391
	Total	19042	44781	
Eastern Basin	Khaf salt marsh	51	415	987
	Hamun lake	52	576	939
	Mashkel	53	298	446
	Total	1289	2372	
Sarakhs Basin	Karakum	60	1432	3276
	Total	1432	3276	
Total (Over all)			47323	105346

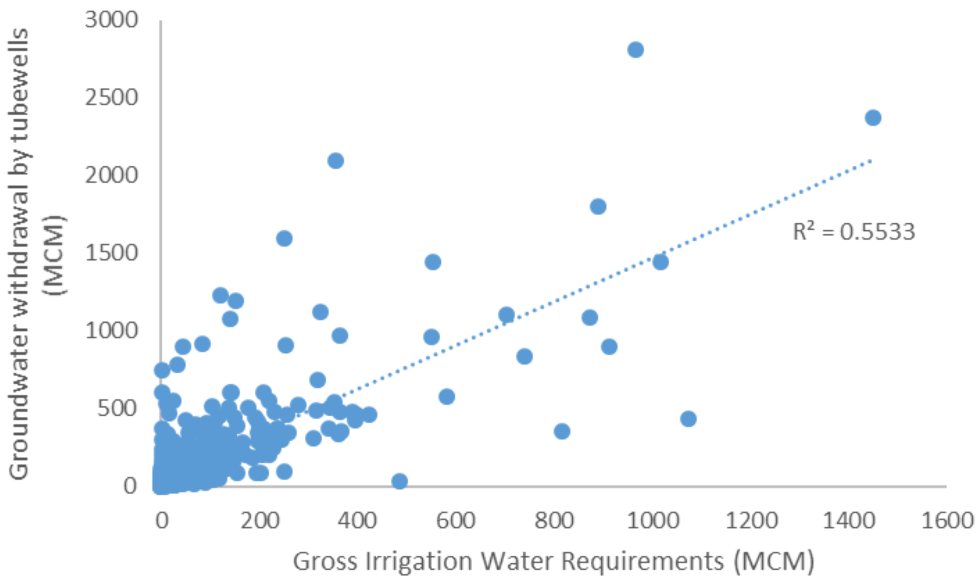

Figure 5. Scatterplot of estimated total gross irrigation requirements (GIR) against the total amount of water withdrawal by agricultural tube-wells.

In addition, the estimated GIR for the major crops was compared with the water requirements reported in the literature review (Table 6 and Figure 6). Most of the relevant research studies published in the Iranian research databases during the last decades was analyzed and the reported NIR was compared with the estimated values. The estimated GIR matches well with the reported NIR and has an acceptable correlation of 0.78 with the results from literature review (Figure 6).

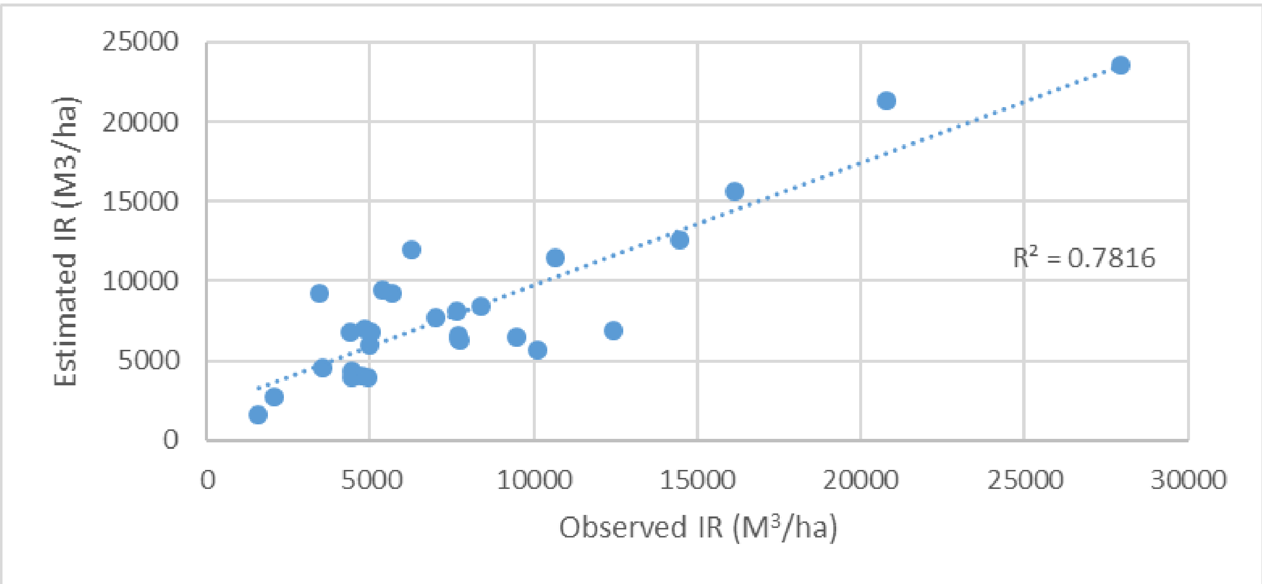

Figure 6. Comparison of GIR with the measured GIR based on field research data (Table 6).

Table 6. Comparison of GIR estimated by developed NWP with the reported GIR in the literature review.

Crop	State (plain code)	Measured GIR (according to reference $m^3\ ha^{-1}$)	Estimated GIR by NWD $m^3\ ha^{-1}$	Reference
Barley	Eastern Azarbayjan (1104)	2060	2750	[19]
	Kerman (4905)	7706	6558	[20]
Sugar beet	Ardebil (1601)	6251	11937	[20]
	Ardebil (1103)	10130	5630	[21]
	Khorasan Razavi (6007)	27941	23615	[22]
	Isfahan (4201)	10660	11510	[23]
	Hamedan (4117)	16161	15608	[24]
Forage corn	Tehran(4134)	14479	12604	[25]
	Kerman (4905)	9473	6472	[20]
Wheat	Lorestan (2208)	5000	5951	[26]
	Fars (4318)	7020	7682	[27]
	Khorasan Razavi (6007)	12460	6887	[28]
	Khozestan (2201)	5655	9248	[29]
	Charmahal-Bakhtiari (2330)	5368	9387	[30]
	Alborz (4133)	7650	8088	[28]
	Khozestan(2201)	3457	9248	[31]
	Kerman (4905)	8391	8376	[20]
	Golestan (1601)	1592	1648	[20]
	Hamedan (4117)	5007	6808	[32]
	Khozestan (2407)	4398	6842	[33]
Rice	Mazandaran (1503)	3540	4520	[34]
	Mazandaran (1403)	4435	4320	[35]
	Mazandaran (1502)	4725	4090	[36]
	Guilan (1202)	4425	3940	[37]
	Guilan (1202)	4916	3940	[38]
Maze	Eastern Azarbayjan (3019)	7754	6270	[39]
	Tehran(4134)	4820	7040	[40]
	Fars (4323)	7680	6390	[41]
Sugar cane	Khozestan (2302)	20780	21340	[42]

3.5. Irrigation efficiency scenarios

Table 7 illustrates the effects of irrigation efficiency and water stress scenarios on the total irrigation water requirement under different climatic conditions. Considering the average efficiency of the irrigation systems operating in Iran (56% scenario), 11.068 MCM water is lost annually because of low irrigation efficiency. By increasing the irrigation efficiency to 65% without considering any water stress, 3.482 MCM of water can be saved. In case of applying 15% water stress, assuming the crop yield remains unchanged, the saved water will reach to 6.732 MCM. The results indicate that if increasing irrigation efficiency is not feasible, 3.772 MCM water can be saved by applying 15% water stress.

Table 7. The effects of water stress scenarios (0 and 15%) and irrigation efficiency (42, 60, and 100%) on the irrigation requirement.

Saved water with/without water stress in MCM						
		No water stress		15% water tress		
	Climate	65%	100%	56%	65%	100%
Wheat	A_Cl_W	157	500	168	302	594
	SH_Cl_W	2	6	2	4	8
	A_Cl_VW	378	1200	434	751	1443
	SA_Cd_W	2	6	2	4	7
	SA_Cl_W	88	281	91	167	332
	A_M_VW	90	286	104	179	344
Rice	A_Cl_W	76	240	91	154	291
	SH_Cl_W	11	35	12	21	42
	A_Cl_VW	144	459	155	278	546
	SA_Cl_W	168	534	173	317	631
	A_M_VW	77	245	70	137	284
Maize	A_Cl_W	87	278	92	167	330
	SH_Cl_W	10	32	11	19	38
	A_Cl_VW	296	941	317	569	1118
	SA_Cl_W	165	525	170	312	620
	A_M_VW	37	119	39	71	140
Sugar beet	A_Cl_W	320	1017	353	624	1214
	SH_Cl_W	4	11	4	7	13
	A_Cl_VW	217	688	237	421	821
	SA_Cd_W	5	16	6	10	20
	SA_Cl_W	193	613	209	373	730
	A_M_VW	24	76	26	46	90
Forage maize	A_Cl_W	227	722	243	436	858
	SH_Cl_W	3	10	3	6	12
	A_Cl_VW	400	1272	431	772	1514
	SA_Cd_W	3	10	3	6	12
	SA_Cl_W	181	574	198	351	685
	A_M_VW	46	147	50	90	176
Sugar cane	A_M_VW	71	225	78	138	269
Total		3482	11068	3772	6732	13182

4. Discussion and conclusions

In this study, web-based water balance simulation tools were developed to estimate the NIR in Iran. The daily water balance components were calculated for the 125 different crops including the dominant strategic crops of winter wheat, barely, rice, maze, sugar beet, and sugarcane in each 609 plains using climatological, crop, and soil data representative for each plain. The web-based simulation model was developed using the FAO-56 dual Kc methodology. Access to the actual irrigated water was nearly impossible in most cases. Therefore, a rate of 15 % water stress was applied to convert the net irrigation water in standard conditions to the actual data. General data on climate, soil, and crop parameters and irrigation management was derived from different national and international sources and was localized by several vast field surveys.

In absence of reference lysimetric data or measured irrigation requirements, the accuracy assessment of the outputs was performed by comparing the estimated NIR with the values found in the literature review. Most of the relevant research studies published in the Iranian research databases during the last decades was analyzed and the reported NIR was compared with the estimated values. In addition, the accuracy of results was evaluated by comparing the estimated GIR with the amount of water withdrawal by agricultural tube-wells in each plain.

In field scale, sugar cane has the highest NIR value (18318 m^3 ha^{-1}) among the studied crops and sugar beet has the second highest (5100–11896 m^3 ha^{-1}). Moreover, the maximum amount of aggregated NIR in plain scale belongs to Qazvin plain and the highest GIR was observed in Tehran-Karaj plain with values of 1.191 and 2.589 MCM, respectively. The aggregated NIR and GIR in scales of sub-basins and main basins indicates that the lowest estimated NIR belongs to the Eastern basin and Mashkel sub-basin with 1.298 and 0.298 MCM, respectively. The highest amounts belong to the Central basin and Namak lake sub-basin with 44.781 and 5.472 MCM, respectively. Total amount of NIR and GIR for the entire country are estimated to be around 47 and 105 BCM. In addition, the results indicate that 3.772 MCM water can be saved by applying 15% water stress. By increasing the irrigation efficiency to 65% without considering any water stress, 3.482 MCM of water can be saved.

The estimated values of 47.323 and 105.346 MCM for NIR and GIR in the current study shows a strong agreement with the literature [5]. Furthermore, the output of the model matches other case studies in different areas of the country and the model proved to be a useful asset in estimation of water requirement of different crops in different climates [19–41]. One of the unexpected results of the study was the poor water management in the northern portion of the plains. An unexpected amount of NIR was detected in those areas, such as Gorgan plain, which can be a sign of unauthorized depletion of renewable water resources

In a comprehensive study, Mirzaie-Nodoushan et al. (2020) reported the total blue water consumption for the croplands in Iran varies between 48.9 and 58.6 BCM under different diets [43]. Karandish et al. (2021) estimated the total blue water consumption value as 45.5 BCM for 27 major crops in Iran which is very consistent with the estimated NIR in the present study. They also mentioned that 78% of this consumption (35.5 BCM) is unsustainable and addressed that the remaining water consumption is used inefficiently [44].

In another study, the relationship of blue and green water consumption with croplands in Iran was analyzed based on designed scenarios by Khorsandi et al (2023) using the methodology proposed by Khorsandi et al. (2022) [45,46]. The results indicate the total water use for producing 19 main crops at the national level varied from 30.47 to 49.91 BCM during 2005–2014. Their results indicate total water consumption in Iran reaches to the 55.27 BCM for an area of 148433.8 km^2 in 2020. The 8.27 BCM difference between our estimation for 2016 and their estimation (55.27–47 BCM) can provide a reasonable estimate of water consumption from rain-fed agriculture in Iran. This rain-fed water consumption is out of human control, and with efficient land management, it can be a sustainable source of agricultural production.

At the same time, Khorsandi et al. (2022) mentioned 77.4 BCM for the total water consumption from 248804.6 km^2 of possible arable lands [46]. This area is the maximum possible land to be used for farming/agriculture in irrigated and rain-fed systems which includes a complete diet and possibly other water usages. The data extracted from Iran's Ministry of Agriculture shows during 2005–2014 the total croplands (both for agriculture and horticulture) was 128039.6–160347.2 km^2. Our results for the maximum amount of water that irrigated agriculture can consume show 47 BCM from an area of 87255 km^2. The difference between our maximum estimation (47 BCM) and their estimate (77.4 BCM) can show the extent of water use by sectors not related to both agriculture and natural reserves.

Ministry of Energy (MoE) estimates for maximum total water consumption in agriculture show 32.8 BCM. Since Karandish et al. (2021) provides net water consumption and MoE provides water withdrawal, their division is a reasonable estimate for the current water efficiency, which is 60% [44]. For efficient agriculture with a cap on water withdrawal, water efficiency should be improved to more than 60–72% levels.

Results indicate that the developed system in this study (NWP) can be considered as a reliable decision-making support tool for the water authorities in making water management decisions, allocating water resources and modifying the cultivation pattern. NWP is a temporary answer to the problem of the absence of reference lysimetric data and national database on the amount of water consumption in agriculture in Iran, which is a vast country with various climatic conditions. Simplicity of use, minimum required input data, and maximum accuracy were the main features of the developed system.

Author contributions

Conceptualization, Majid Vazifedoust, Mohammadreza Keshavarz, Ali Mokhtari, Elham Barikani and Mojtaba Palouj; Methodology, Majid Vazifedoust, Mohammadreza Keshavarz and Ali Mokhtari; Software, Majid Vazifedoust; Validation, Majid Vazifedoust, Mohammadreza Keshavarz and Ali Mokhtari; Formal analysis, Majid Vazifedoust; Investigation, Majid Vazifedoust, Mohammadreza Keshavarz, Ali Mokhtari, Elham Barikani and Mojtaba Palouj; Resources, Majid Vazifedoust; Data curation, Elham Barikani and Mojtaba Palouj; Writing-original draft preparation, Ali Mokhtari; Writing-review and editing, Majid Vazifedoust and Mohammadreza Keshavarz; Visualization, Ali Mokhtari; Supervision, Majid Vazifedoust; Project administration, Majid Vazifedoust. All authors have read and agreed to the published version of the manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

References

1. Ebrahimi P (2022) Chapter 14—Analysis of social resilience of villagers in the face of drought using LPCIEA indicator case study: Downstream of Dorodzan dam. In: Pourghasemi HR (Ed.), *Computers in Earth and Environmental Sciences,* Elsevier, 199–219. https://doi.org/10.1016/B978-0-323-89861-4.00039-7

2. Mokarram M, Pourghasemi HR, Hu M, et al. (2021) Determining and forecasting drought susceptibility in southwestern Iran using multi-criteria decision-making (MCDM) coupled with CA-Markov model. *Sci Total Environ* 781: 146703. https://doi.org/10.1016/j.scitotenv.2021.146703
3. Mafi-Gholami D, Zenner EK, Jaafari A, et al. (2020) Spatially explicit predictions of changes in the extent of mangroves of Iran at the end of the 21st century. *Estuarine, Coastal Shelf Sci* 237:106644. https://doi.org/10.1016/j.ecss.2020.106644
4. Mesgaran MB, Madani K, Hashemi H, et al. (2017) Iran's land suitability for agriculture. *Sci Rep* 7: 7670. https://doi.org/10.1038/s41598-017-08066-y
5. Abasi F, Naseri A, Sohran F, et al. (2015) Official Report: Improvement of water consumption efficiency. Agricultural Research Education and Extension Organization of IRAN.
6. Saemian P, Tourian MJ, AghaKouchak A, et al. (2022) How much water did Iran lose over the last two decades? *J Hydrol: Reg Stud* 41: 101095. https://doi.org/10.1016/j.ejrh.2022.101095
7. Pirmoradian N, Davatgar N (2019) Simulating the effects of climatic fluctuations on rice irrigation water requirement using AquaCrop. *Agric Water Manag* 213: 97–106. https://doi.org/10.1016/j.agwat.2018.10.003
8. United Nations Educational, Scientific and Cultural Organization (UNESCO) (1979) Map of the world distribution of arid regions: Explanatory note. Paris, 54.
9. Allen RG, Pereira LS, Raes D, et al. (1998) Crop Evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome* 300: D05109.
10. Shahrokhnia MH, Sepaskhah AR (2013) Single and dual crop coefficients and crop evapotranspiration for wheat and maize in a semi-arid region. *Theor Appl Climatol* 114: 495–510. https://doi.org/10.1007/S00704-013-0848-6
11. Doorenbos J (1977) Guidelines for predicting crop water requirements. *FAO Irrig Drain Pap* 24: 1–179.
12. Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. *Appl Eng Agric* 1: 96–99. https://doi.org/10.13031/2013.26773
13. Rosa RD, Paredes P, Rodrigues GC, et al. (2012) Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. *Agric Water Manag* 103: 8–24. https://doi.org/10.1016/j.agwat.2011.10.013
14. Liu Y, Luo Y (2010) A consolidated evaluation of the FAO-56 dual crop coefficient approach using the lysimeter data in the North China Plain. *Agric Water Manag* 97: 31–40. https://doi.org/10.1016/j.agwat.2009.07.003
15. Phogat V, Šimůnek J, Skewes MA, et al. (2016) Improving the estimation of evaporation by the FAO-56 dual crop coefficient approach under subsurface drip irrigation. *Agric Water Manag* 178: 189–200. https://doi.org/10.1016/j.agwat.2016.09.022
16. Paredes P, Rodrigues GJ, Petry MT, et al. (2018) Evapotranspiration partition and crop coefficients of Tifton 85 Bermudagrass as affected by the frequency of cuttings. Application of the FAO56 Dual Kc Model. *Water* 10: 558. https://doi.org/10.3390/W10050558
17. Abasi F, Sohrab F, Abasi N (2017) Evaluation of irrigation efficiencies in Iran. *Irrig Drain Struct Eng Res* 17: 113–120. https://doi.org/10.22092/aridse.2017.109617
18. Mokhtari A, Noory H, Vazifedoust M, et al. (2019) Evaluation of single crop coefficient curves derived from Landsat satellite images for major crops in Iran. *Agric Water Manag* 218: 234–249. https://doi.org/10.1016/j.agwat.2019.03.024

19. Nasiri A (2014) Water requirements of wheat and barley in Ahar. *J Dev Geo* 107: 35–40.
20. Heydari N (2011) Determination and evaluation of water use efficiency of some major crops under farmers management in Iran, *J Water Irrig Manag* 1: 43–57. https://jwim.ut.ac.ir/article_24582.html?lang=en
21. Raoof M (2019) Determination of sugar beet crop coefficient using lysimeter in Ardabil Plain and its comparison with FAO global data. *J Water Res Agric* 33: 175–188. https://doi.org/10.22092/jwra.2019.119736
22. Shahabifar M, Rahimian M (2008) Measurement of sugar beet water requirements by lysimeter method in Mashhad. *J Sugar Beet* 23: 177–184. https://www.sid.ir/en/journal/ViewPaper.aspx?id=120647
23. Panahi M, Agdaei M, Rezaei M (2006) Determination of sugar beet standard evapotranspiration by lysimeter method in Kabotar-Abad, Esfahan. *J Sugar Beet* 22: 37–25. https://doi.org/10.22092/jsb.2006.1663
24. Zare Abyaneh H, Farrokhi E, Bayat Varkeshi M, et al. (2011) Determination of water requirement and the effect of the changes on some quantitative and qualitative characteristics of products of sugar beet. *J Sugar Beet* 27: 153–167. https://www.sid.ir/en/journal/ViewPaper.aspx?id=263798
25. Gheysari M, Mirlatifi SM, Homaee M, et al. (2006) Determination of crop water use and crop coefficient of corn silage based on crop growth stages. *J Agric Eng Res* 7: 125–142.
26. Sepahvand M (2009) Comparison of water requirement, water productivity and economical water productivity of wheat and rapeseed in the west of Iran in wet years. *Iran Water Res J* 3: 63–68. https://www.sid.ir/en/journal/ViewPaper.aspx?id=176386
27. Niazi JA, Fouladmand HR, Ahmadi SH, et al. (2005) Water requirement and crop coefficient of wheat in Zarghan area, Fars Province. *J Sci Technol Agric Natl Resour* 9: 1–9. https://www.sid.ir/en/journal/ViewPaper.aspx?id=34199
28. Ghaemi M, Raeini Sarjaz M, Mosavi M (2013) Estimating the crop coefficient and the water requirement of the Gascogne wheat by using energy balance method in Mashhad. *Iran J Irrig Water Eng* 3: 58–68. https://www.sid.ir/en/journal/ViewPaper.aspx?id=378207
29. Kamaledin H, Dahanzadeh B (2014) Evaluation of irrigation water saving amount in the wheat cultivation in Ahvaz City. *J Water Eng* 2: 75–86. https://jwe.shoushtar.iau.ir/article_529611.html
30. Haghighati B (2013) Report of the Promotion Plan—Improving management and optimal water consumption in the process of producing agricultural products. Agricultural and Natural Resources Research Center of Chaharmahal and Bakhtiari. Persian with English abstract.
31. Absalan S, Heydari N, Sedaghat M (2011) Evaluation of water productivity in the saline areas of lower karkheh basin and determination of its causes: a study from southern Iran. *Cercetări Agronomice în Moldova* XLIV 3.
32. Ghasemi Nejad Raeini MR, Maroufi S, Zare Kohan M, et al. (2012) Study of water productivity index and its comparison with current conditions of wheat fields. *Irrig Sci Eng* 1: 71–77. https://sid.ir/paper/217063/fa
33. Salamati N, Baghani J, Abbasi F (2018) Determination of wheat water productivity in sprinkler and surface irrigation systems (Case Study in Behbahan). *Iran J Soil Water Res* 49: 821–830. https://www.sid.ir/en/journal/ViewPaper.aspx?id=653251
34. Gholami Sefidkouhi MA, Bagheri Khalili Z, GhaleNovi MA (2021) Investigation of rice actual evapotranspiration and crop coefficients for Shiroudi and Hashemi cultivars in Sari. *J Water Res Agric* 36: 505–515. https://doi.org/10.22092/jwra.2021.123620

35. Jalali Koutenaei N, Shahnazari A, Ziatabar Ahmadi MK, et al. (2021) Estimation of water requirement and crop coefficients of rice cultivars Kuhsar and Hashemi in different cultivation systems. *J Water Res Agric* 35: 235–245. https://doi.org/10.22092/jwra.2021.352374.833
36. Shahnazari A, Ziatabar Ahmadi M, Aghajani mazandarani G (2012) The comparison of water balance parameters in traditional and leveled paddy fields in Qaemshahr, Iran. *Water Soil* 26: 1010–1017. https://doi.org/10.22067/jsw.v0i0.15305
37. Modabberi H, Mirlatifi M, Gholami MA (2014) Determination of evapotranspiration and crop coefficient of two rice cultivars in Mordab Plain (Guilan Province). *J Hydrol Soil Sci* 18: 95–106.
38. Pirmoradian N, Zekri F, Rezaei M, et al. (2013) Derivation of crop coefficients of three rice varieties based on ETo estimation method in Rasht region. *Cereal Res* 3: 95–106. https://cr.guilan.ac.ir/article_1603.html
39. Majnooni-Heris A, Nazemi AH, Sadraddini AA, et al. (2012) Evaluation of Maize Simulation Model (MSM2) by Lysimetric Data. *J Water Soil Sci* 22: 55.
40. Mashal M, Varavypour M, Sadatnouri SA, et al. (2009) Optimizing consumptive water depth for corn by deficit-irrigation (Case Study: Varamin area). *J Agric Res (Water, Soil and Plants in Agriculture)* 8: 123–134.
41. Zand-Parsa SH, Soltani GHR, Sepaskhah AR (2001) Determination of optimum irrigation depth of corn in sprinkler irrigation. *J Hydrol Soil Sci* 5: 1–7.
42. Sheini Dashtegol A, Hamoodi M (2009) Studying the water requirement and plant coefficients of sugarcane by lysimetric method in the sugarcane lands of South Ahvaz. The *11th Iranian Soil Science Congress*,Gorgan. Available from: https://civilica.com/doc/291596/.
43. Mirzaie-Nodoushan F, Morid S, Dehghanisanij H (2020) Reducing water footprints through healthy and reasonable changes in diet and imported products. *Sustain Prod Consum* 23: 30–41. https://doi.org/10.1016/j.spc.2020.04.002
44. Karandish F, Nouri H, Brugnach M (2021) Agro-economic and socio-environmental assessments of food and virtual water trades of Iran. *Sci Rep* 11: 15022. https://doi.org/10.1038/s41598-021-93928-9
45. Khorsandi M, Omidi T, Van Oel P (2023) Water-related limits to growth for agriculture in Iran. *Heliyon* 9: e16132. https://doi.org/10.1016/j.heliyon.2023.e16132
46. Khorsandi M, Homayouni S, Van Oel P (2022) The edge of the petri dish for a nation: Water resources carrying capacity assessment for Iran. *Sci Total Environ* 817: 153038. https://doi.org/10.1016/j.scitotenv.2022.153038

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