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Modeling wheat yield and crop water productivity in Iran: Implications of agricultural water management for wheat production

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ABSTRACT

In most parts of Iran, water scarcity has been intensifying and posing a threat to the sustainability of agricultural production. Wheat is the dominant crop and the largest irrigation water user in Iran; hence, understanding of the crop yield–water relations in wheat across the country is essential for a sustainable production. Based on a previously calibrated hydrologic model, we modeled irrigated and rainfed wheat yield (*Y*) and consumptive water use (*ET*) with uncertainty analysis at a subbasin level in Iran. Simulated *Y* and *ET* were used to calculate crop water productivity (*CWP*). The model was then used to analyze the impact of several stated policies to improve the agricultural system in Iran. These included: increasing the quantity of cereal production through more efficient use of land and water resources, improving activities related to soil moisture conservation and retention, and optimizing fertilizer application. Our analysis of the ratio of water use to internal renewable water resources revealed that 23 out of 30 provinces were using more than 40% of their water resources for agriculture. Twelve provinces reached a ratio of 100% and even greater, indicating severe water scarcity and groundwater resource depletion. An analysis of *Y-CWP* relationship showed that one unit increase in rainfed wheat yield resulted in a lesser additional water requirement than irrigated wheat, leading to a larger improvement in *CWP*. The inference is that a better water management in rainfed wheat, where yield is currently small, will lead to a larger marginal return in the consumed water. An assessment of improvement in soil available water capacity (*AWC*) showed that 18 out of 30 provinces are more certain to save water while increasing *AWC* through proper soil management practices. As wheat self-sufficiency is a desired national objective, we estimated the water requirement of the year 2020 (keeping all factors except population constant) to fulfill the wheat demand. The results showed that 88% of the additional wheat production would need to be produced in the water scarce provinces. Therefore, a strategic planning in the national agricultural production and food trade to ensure sustainable water use is needed. This study lays the basis for a systematic analysis of the potentials for improving regional and national water use efficiency. The methodology used in this research, could be applied to other water scarce countries for policy impact analysis and the adoption of a sustainable agricultural strategy.

1. Introduction

It is widely recognized that population growth and economic development will lead to an increasing competition for scarce water resources (Molden, 1997; Seckler et al., 1998; Rockstrom et al., 2009). Irrigated agriculture as the largest water-consuming sector faces challenge to produce more food with less water. Increasing crop water productivity (*CWP*) is necessary to meet the challenge (Kijne et al., 2003). A sound knowledge of *CWP* and water resources availability at fine spatial and temporal resolution is, therefore, of importance for understanding the water and food relationship and for assessing the feasibility of the virtual water strategy in improving water use efficiency in a country (Yang and Zehnder, 2007).

Iran as a whole is a water scarce country. Most regions of the country are faced with water shortages. There are calls at the Government level to improve crop water productivity as a way of mitigating water scarcity in Iran (NRC, 2005; Alizadeh and Keshavarz, 2005). However, the question of how to improve water productivity is rather complex given the agronomic, hydrogeologic, and socio-economic conditions in the country. Although

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self-sufficiency has been a national objective for wheat and the goal was achieved in 2004 (Deihimfard et al., 2007), there are continuing questions to Iran's ability to sustain its wheat production. Growing scarcity of water resources and the frequent and prolonged droughts are the main reasons for this concern.

Agriculture in Iran uses more than 90% of the developed water resources (Alizadeh and Keshavarz, 2005). However, quantitative studies on water resources and irrigated agriculture on the river-basin scale have so far only been conducted for two out of 37 main river basins in Iran, i.e., Zayandeh Rud river basin (Salemi et al., 2000; Akbari et al., 2007) and Karkheh river basin (Ghafouri, 2007). A long-term policy and strategy for national water resources management is to "establish a comprehensive water management system that incorporates natural elements of the total water cycle as part of principles of sustainable development" (Ardakanian, 2005). With this background, developing a model for a systematic assessment of water resources availability, agricultural water use, crop yield as well as *CWP* at fine spatial and temporal resolution would be useful to better understand water and food relations and the challenges faced by the country.

Different models have been applied in the literature of water–crop yield relations. Very broadly, they can be divided into two categories: empirical and process-based models. The main drawback of the empirical models is that they are mostly regression-based models where a correlation is established between the statistical crop yield and local weather related, geo-statistical related, and management related (e.g., irrigation) factors. Therefore, they are capable of predicting only yield. Prediction of crop water uptake and soil evaporation is lacking. Some examples of the process-based models are Soil Water Atmosphere Plant (SWAP) (Singh et al., 2006; Vazifedoust et al., 2007), Soil Vegetation Atmosphere Transfer (SVAT) (Mo et al., 2005), GIS-based Environmental Policy Integrated Climate model GEPIC (Liu et al., 2007a), InfoCrop (Aggarwal et al., 2006), and WaterGAP (Alcamo et al., 2003). The process-based models are often either strong in crop growth simulation or in hydrology. A key limitation in many of these models is that the crop yield and consumptive water use modeled for a given area are not linked with water resources availability of that area. Therefore, one cannot assess directly the aggregate impact of regional water resources availability, landuse change, and climate change on crop production. Furthermore, most of the existing studies using process-based models are not calibrated and validated. To the best of our knowledge, there are only few studies (e.g., Challinor and Wheeler, 2008; Iizumi et al., 2009) that account for model related uncertainties in crop yield prediction.

In a previous work (Faramarzi et al., 2009), a hydrological model of Iran was developed using the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). In the present study, we extended the hydrological calibrated model of Iran to model crop yield. The hydrology and crop growth modules in SWAT provide the basis for an integrated study of soil-crop-atmosphere processes. Our major objectives were: (i) to model the spatial and temporal variability of crop yield as well as crop consumptive water use with uncertainty analysis for wheat at a subbasin level, and subsequently calculate *CWP*; (ii) to calibrate (1990–2002) and validate (1980–1989) crop yield and to highlight the differences in irrigated and rainfed wheat systems. As statistical data was only available at the provincial level, the calibration and validation could only be performed at provincial level; (iii) to analyze the current status of water demand and water supply situation in Iran at provincial and national levels to lay a basis for discussing Iran's water and agricultural future; and finally (iv) to show how the current study could be used for analyzing policy implications.

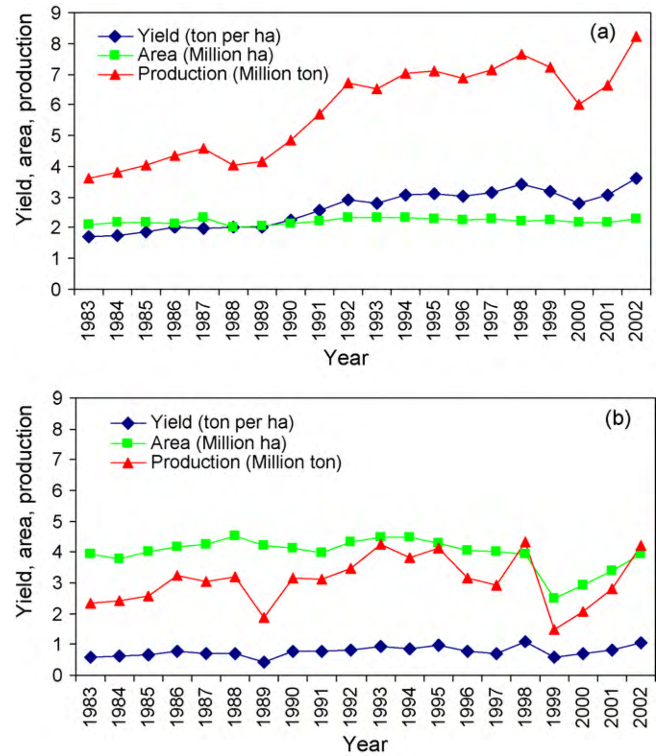

Fig. 1. Historical yield, area, and production for (a) irrigated wheat, and (b) rainfed wheat. The large dip in the production reflects the severe drought event during 1999–2001.

2. Materials and methods

2.1. Description of the study area

Geographically, Iran is located between 25–40°N latitude and 44–63°E longitude with total area of about 1.648 million km^2. Climatic conditions of Iran are mostly typical of arid and semi-arid regions. Nevertheless, the country has a wide spectrum of climatic, physiographic, edaphic, and hydrological conditions.

Agricultural areas are distributed across 30 provinces in the country. Roughly 12% of country's land surface or 18.5 million hectares are devoted to field crop production and horticulture (Alizadeh and Keshavarz, 2005). About 9 million hectares of this land are irrigated using traditional and modern techniques, around 6.5 million hectares are rainfed, and the rest is fallow. The most extensive cultivated area is devoted to wheat. Wheat is grown on nearly 60% of the total country's area under cultivation. Fig. 1 gives an overview of the country's historical wheat yield, crop area, and production. The large dip in the production in 1999 was due to a severe drought where many major rivers such as Zayandeh Rud were dried up in the country.

Both irrigated and rainfed farming systems are practiced in different parts of the country while the area devoted to each system varies considerably depending on agro-climatic conditions. Surface water use has been increased by construction of numerous multi-purpose dams and reservoirs along rivers flowing from the Zagros and Alburz mountains. Groundwater is the main source of potable water in most areas in the central, northeastern and southern parts of the country. Since the groundwater is intensively extracted to meet the water demand of crops, the groundwater table has been declining significantly in most parts of Iran (Mousavi, 2005; Pazira and Sadeghzadeh, 1999).

In the vast desert areas of the country, no agricultural activity is practiced because of harsh climatic conditions, particularly lack of

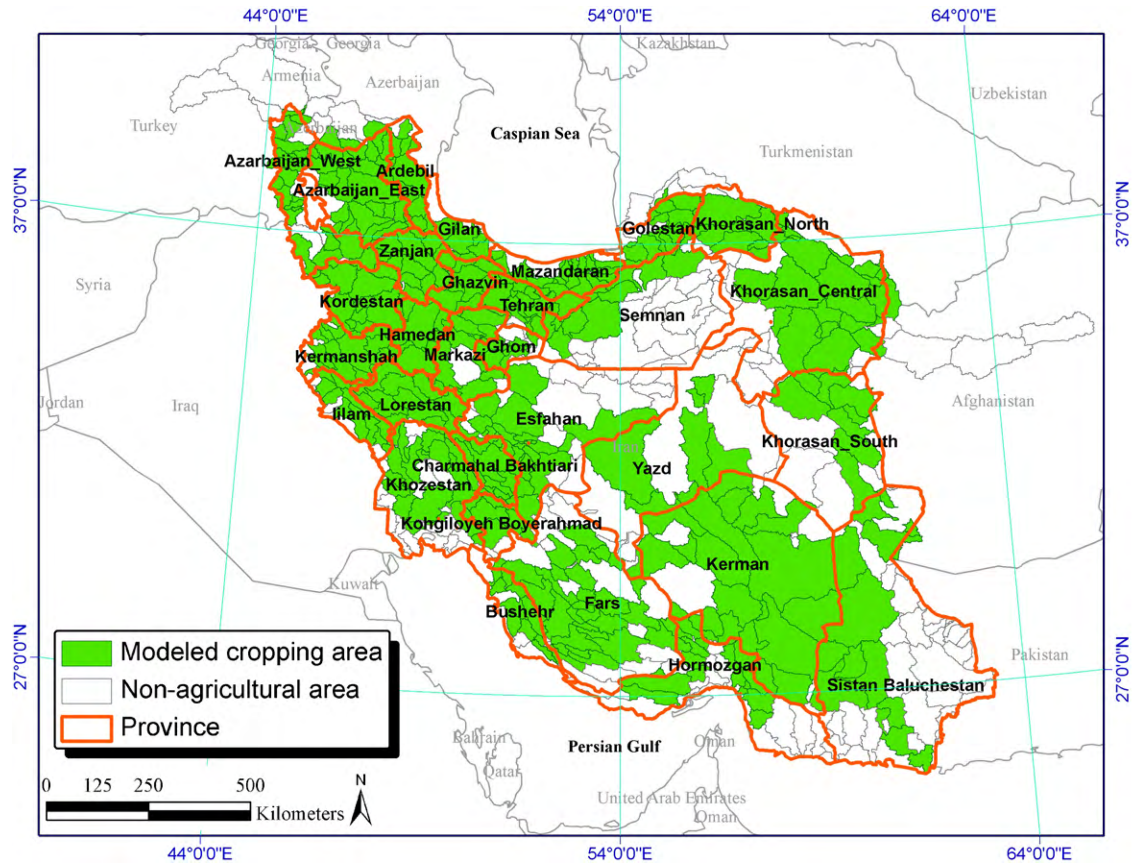

Fig. 2. Study area and the modeled subbasins where wheat is grown.

water. This study only considered the subbasins where crop production is practiced. The modeled area and the names of provinces are shown in Fig. 2.

2.2. The SWAT model

SWAT is a basin scale, continuous-time model that operates on a daily time step and is developed to predict the impact of land management practices on water, sediment, and nutrient yields in large complex watersheds with varying soils, landuses, and management conditions. The program has been successfully used in a wide range of scales and environmental conditions from small catchments to continental level (Gassman et al., 2007). It simulates plant growth processes as well as water quantity and water quality processes. In this study, we used ArcSWAT (Olivera et al., 2006), where ArcGIS (ver. 9.1) environment is used for project development.

Spatial parameterization of the SWAT model is performed by dividing the watershed into subbasins based on topography. These are further subdivided into a series of hydrologic response units (HRU) based on unique soil and landuse characteristics. The responses of each HRU in terms of water and nutrient transformations and losses are determined individually, aggregated at the subbasin level and routed to the associated reach and catchment outlet through the channel network. The local water balance for each unit is simulated for four storage volumes including snow, soil profile, shallow aquifer, and deep aquifer.

The crop growth component of SWAT, which is a simplified version of EPIC model (Williams, 1995), is capable of simulating a wide range of crop rotation, grassland/pasture systems, and trees. In the SWAT model, potential crop growth and yield are usually not achieved as they are inhibited by temperature, water, nitrogen and phosphorus stress factors. Actual yield is calculated by multiplying actual aboveground biomass (bio_{act}) and actual harvest index (HI_{act}). Harvest index (HI) is the fraction of aboveground plant dry biomass that is removed as dry economic yield. In a given area, bio_{act} is affected by all management stress factors (water, fertilizer, and temperature), while HI_{act} is affected only by water-stress factor. The latter can be calibrated to achieve a certain water-stress-limited yield. There are two options for application of irrigation water and timing of fertilization: user specified and automatic. In the automatic option, an irrigation event is triggered based on a water-stress threshold, while fertilizer timing is based on a nitrogen stress factor. The total amount of fertilizer use during the growing season is the amount of fertilizer specified by the user per year. Plant growth is determined from leaf area development, light interception, and conversion of intercepted light into biomass assuming crop-specific radiation use efficiency. A more detailed description of the model is given by Neitsch et al. (2002).

2.3. Model parameterization and input data

Spatial parameterization in this project was performed by dividing the watershed into subbasins based on topography and dominant soil, landuse, and slop. This resulted in a total of 506 subbasins covering the whole country. Surface runoff was simulated using the USDA SCS curve number (CN) method (USDA SCS, 1972).

We selected automatic irrigation and fertilization option in this study because of the difficulty in obtaining irrigation and fertilization schedule data for different provinces. This is the case for most of the studies dealing with large-scale crop growth simulation (e.g., Liu et al., 2007a; Liu, 2009; Yun, 2003). For each province, the cropping calendar was based on the long-term average available planting and harvesting dates in the provinces from the Iranian Ministry of Jahade-Agriculture (MOJA) and reports by FAO. We

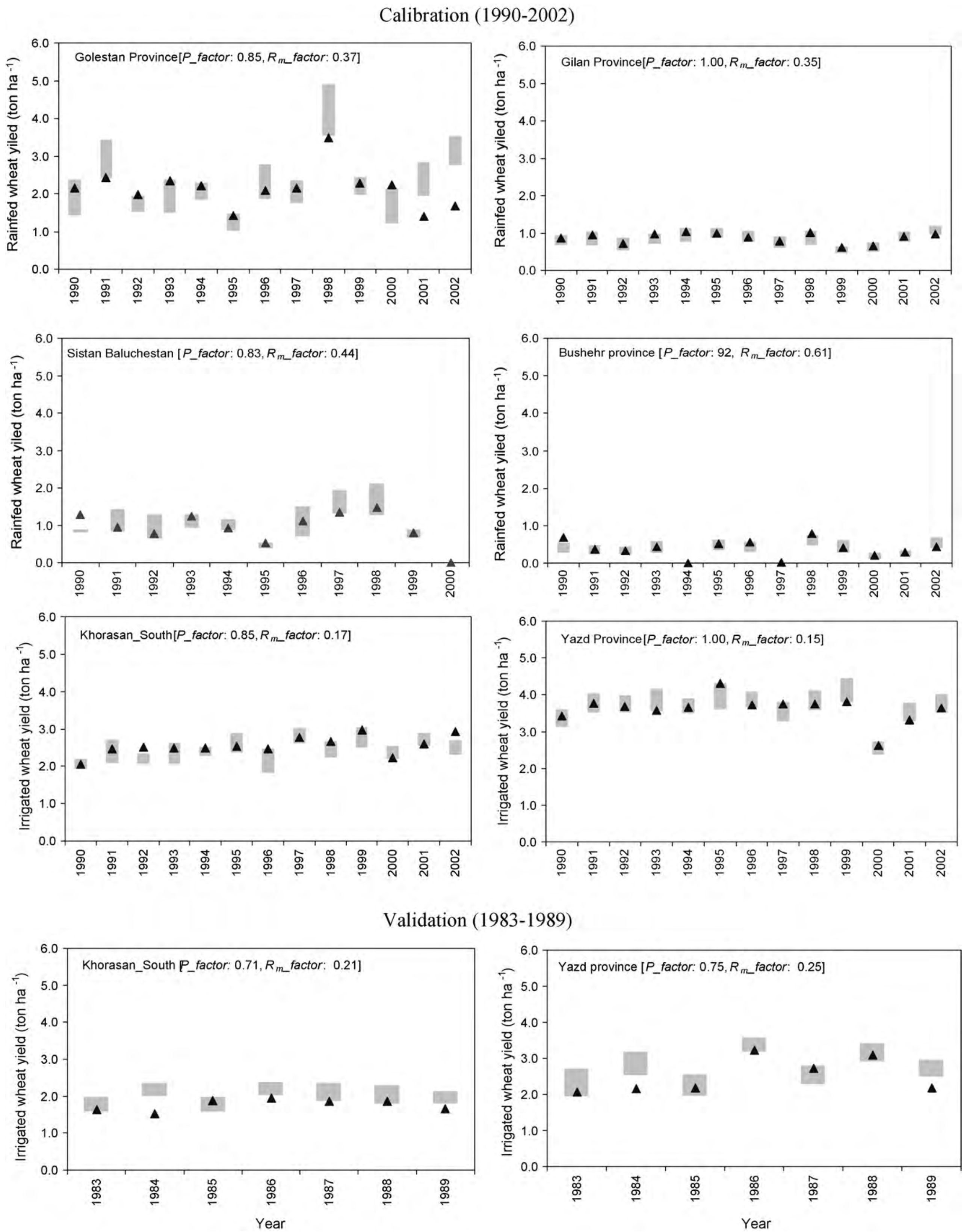

Fig. 3. Comparison of observed (blue points) and simulated (expressed as 95% prediction uncertainty band) yield for four selected provinces in rainfed wheat and two provinces in irrigated wheat regions. Calibration and validation results are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 1
Final wheat yield calibration statistics for different provinces.

Province	Rainfed wheat		Irrigated wheat	
	P-factor[a]	R_m*-factor*[b]	*P-factor*	R_m*-factor*
Ardebil	1.00	0.61	1.00	0.41
Azarbaijan_East	1.00	0.47	0.92	0.22
Azarbaijan_West	0.85	0.57	1.00	0.39
Bushehr	1.00	0.61	0.85	0.36
Charmahal	1.00	1.09	1.00	1.56
Esfahan	0.85	0.33	0.70	0.36
Fars	0.85	1.01	0.70	0.15
Ghazvin	0.91	0.48	0.82	0.24
Ghom	1.00	1.51	1.00	0.12
Gilan	1.00	0.36	0.85	0.59
Golestan	0.85	0.38	0.85	0.19
Hamedan	1.00	0.78	0.70	0.16
Hormozgan	0.92	0.45	0.85	0.19
Iilam	0.92	1.04	1.00	1.06
Kerman	0.85	0.96	0.92	0.12
Kermanshah	1.00	1.09	1.00	0.69
Khorasan_Central	1.00	1.40	0.77	0.23
Khorasan_North	1.00	0.57	0.70	0.34
Khozestan	0.92	0.43	0.92	0.81
Khorasan_South	NA[c]	NA	0.85	0.17
Kohgiloyeh	1.00	1.13	1.00	0.84
Kordestan	1.00	0.97	0.92	0.44
Lorestan	1.00	1.05	1.00	0.84
Markazi	1.00	0.36	0.70	0.31
Mazandaran	1.00	0.38	0.77	0.66
Semnan	0.92	0.39	0.92	0.20
Sistan Baluchestan	0.77	0.45	0.85	0.51
Tehran	1.00	0.69	0.92	0.28
Yazd	NA	NA	1.00	0.15
Zanjan	0.92	0.754	1.00	0.29

[a] *P-factor* is the percentage of data bracketed by the 95% prediction uncertainty (95PPU).
[b] R_m*-factor* is the ratio of average width of the 95PPU divided by the mean of the variable.
[c] NA means rainfed wheat not grown in this province.

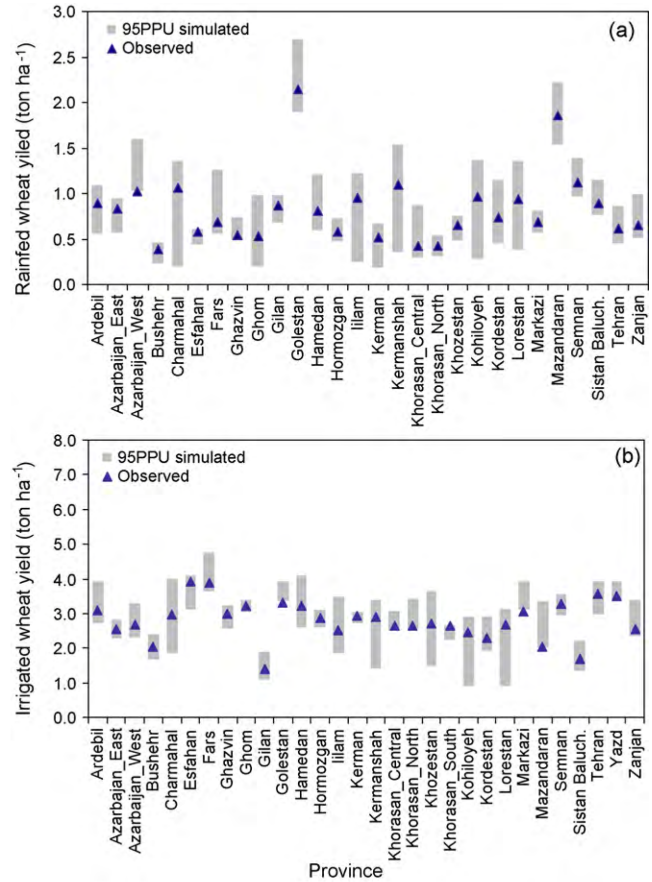

Fig. 4. Comparison of the average annual (1990–2002) observed and 95PPU of simulated yield for (a) rainfed and (b) irrigated wheat shown for different provinces.

chose the method of Hargreaves for calculation of potential evapotranspiration and the methodology developed by Ritchie (1972) for calculation of actual evapotranspiration (AET). Leaf area index (LAI) and root development were simulated on daily time steps. The daily value of LAI was used to partition PET into potential soil evaporation and potential plant transpiration. Average cumulative heat unit was assumed to be around 2300 for wheat (Khodabandeh, 2005). Sixteen years of data (1987–2002) were used for model calibration considering 3 years as the warm-up period. The warm-up period is used for equilibration of hydrological cycle to mitigate the unknown initial conditions and is excluded from the analysis. For validation, the data from 1977 to 1989 were used also with 3 years as warm-up period.

Data required in this study were obtained from the following sources:

i. *Historical annual yield and area cultivated* with cereal crops were obtained for the period of 1977 to 2002 from the Agricultural Statistics and the Information Center of Ministry of Jahade-Agriculture (MOJA) and Statistical Center of Iran (SCI).
ii. Provincial fertilizer use, fertilizer ratio, and planting-harvesting date by crop were obtained from reports published by MOJA and partly from FAO (2005).
iii. *The irrigation map* was constructed from the Global Map of Irrigation Areas of the Food and Agriculture Organization of the United Nations (Siebert et al., 2007) http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index10.stm, which was developed by combining sub-national irrigation statistics with geospatial information on the position and extent of irrigation schemes.

For more detail on the hydrological data requirement and model development the readers are referred to Faramarzi et al. (2009).

2.4. Estimation of crop water productivity (CWP)

CWP combines physical accounting of water with yield or economic output to indicate the value of a unit of water. In this study, it was calculated as:

$$CWP = \frac{Y}{ET} \quad (1)$$

where *CWP* is the crop water productivity in $\mathrm{kg\,m^{-3}}$, *Y* is the crop yield in $\mathrm{kg\,ha^{-1}}$, and *ET* is the seasonal evapotranspiration in $\mathrm{m^3\,ha^{-1}}$, assumed here to be the crop's consumptive water use.

In this study, *Y* is annual yield and *ET* is calculated on a monthly basis. The spatial resolution of *Y*, *ET*, and *CWP* is at a subbasin level, but for comparison with other studies and the available statistics, the modeled results were aggregated to provincial level. It is noteworthy that the above definition of *CWP* does not account for water wasted due to irrigation inefficiencies.

2.5. Calibration setup and uncertainty analysis

Calibration, validation and uncertainty analysis were performed in this study using historical crop yield. Simulated crop yield is most sensitive to two groups of parameters/factors (Ruget et al., 2002; Wang et al., 2005; Ziaei and Sepaskhah, 2003): (i) parameters affecting both hydrology and crop growth processes like available water capacity (*AWC*), SCS curve number index (*CN*), and (ii) factors sensitive only to crop growth processes like harvest index (*HI*), heat unit (*HEAT-UNITS*), water-stress factor (*AUTO-WSTRS*), nitro-

Table 2
The crop related parameters included in the calibration procedure and their final ranges. Similar initial parameter ranges were used for both rainfed and irrigated wheat. These are: actual harvest index (HI_{act}): 0.00–1.00, and potential heat units (*HEAT-UNITS*): 1300–3000.

Province	Rainfed wheat		Irrigated wheat	
	HI_{act}	*HEAT-UNITS*	HI_{act}	*HEAT-UNITS*
Ardebil	0.15–0.22	1200–1600	0.25–0.33	1800–2000
Azarbajan_East	0.08–0.12	1300–1500	0.19–0.22	1900–2000
Azarbaijan_West	0.00–0.32	1300–1500	0.27–0.28	2000–2100
Bushehr	0.03–0.15	1600–2000	0.30–0.4	2100–2300
Charmahal	0.21–0.33	1900–2000	0.29–0.32	2000–2400
Esfahan	0.00–0.26	1500–2000	0.35–0.39	2200–2300
Fars	0.10–0.20	1500–1600	0.33–0.37	2300–2500
Ghazvin	0.10–0.14	1500–1700	0.23–0.27	2200–2400
Ghom	0.10–0.50	1500–2000	0.32–0.34	2300–2500
Gilan	0.05–0.29	1500–1850	0.11–0.17	2200–2400
Golestan	0.00–0.69	1500–2500	0.26–0.31	2200–2400
Hamedan	0.20–0.32	1500–2000	0.21–0.33	2200–2500
Hormozgan	0.05–0.35	1500–2000	0.35–0.38	2200–2500
Iilam	0.33–0.37	1500–2000	0.37–0.48	1900–2000
Kerman	0.00–0.20	1600–1900	0.24–0.26	2100–2600
Kermanshah	0.21–0.36	1500–2000	0.36–0.38	2000–2500
Khorasan_Central	0.06–0.18	1600–1850	0.25–0.3	2300–2600
Khorasan_North	0.08–0.60	1650–2000	0.32–0.35	2100–2500
Khorasan_South	NA[a]	NA	0.15–0.17	2000–2300
Khozestan	0.01–0.55	1500–2000	0.51–0.58	2300–2500
Kohiloyeh	0.38–0.41	1500–2000	0.37–0.38	2100–2300
Kordestan	035–0.38	1600–1700	0.30–0.33	1900–2100
Lorestan	0.35–0.37	1500–1850	0.35–0.43	2000–2400
Markazi	0.04–0.23	1500–2000	0.27–0.35	2000–2400
Mazandaran	0.20–0.29	1500–2000	0.17–0.27	1900–2300
Semnan	0.05–0.61	1500–2000	0.27–0.32	2000–2400
Sistan Baluchestan	0.00–0.65	1500–2300	0.12–0.19	2400–2600
Tehran	0.10–0.18	1500–1900	0.22–0.30	2200–2400
Yazd	NA	NA	0.36–0.41	2200–2500
Zanjan	0.18–0.30	1500–2000	0.15–0.22	2000–2400

[a]NA means rainfed wheat not grown in this province.

gen stress factor (*AUTO-NSTRS*), and planting-harvesting dates. To model the crop yield we calibrated first the hydrology (Faramarzi et al., 2009) followed by the calibration of the yield parameters. Accordingly we used the optimized parameters of hydrology which includes also parameters sensitive to crop growth (i.e., *AWC*, and *CN*) and calibrated in this study the two sensitive parameters to crop yield (i.e., *HI* and *HEAT-UNITS*).

The SUFI-2 program in the SWAT-CUP package (Abbaspour, 2007) was used for parameter optimization. In the SUFI-2 stochastic optimization, parameter non-uniqueness (or parameter uncertainty) is also addressed simultaneously along with the calibration process. Using SUFI-2, all sources of uncertainty are mapped to a set of parameter ranges. Initial and final parameter ranges as well as final simulation results are always expressed as distributions. For this reason, statistics such as R^2 or Nasch-Sutcliffe (*NS*), which compare two signals, are not adequate for calculation of goodness of fit. The SUFI-2 algorithm uses two different indices to quantify the goodness of calibration/uncertainty performance (Abbaspour et al., 2004, 2007). First, the *P-factor*, which is the percentage of data bracketed by the 95% prediction uncertainty (95PPU) band (maximum value 100%) calculated at the 2.5% and 97.5% levels of the cumulative distribution of a variable obtained through Latin hypercube sampling of the parameter spaces. Second, the *R-factor*, which in this study is referred as R_m-*factor*, is calculated as the average width of the uncertainty band divided by the mean of the corresponding measured variable. Normally, standard deviation is used in the calculation of *R-factor* (Abbaspour, 2007). Ideally, we would like to bracket most of the measured data (plus their uncertainties) within the 95PPU band (*P-factor* → 1) while having the narrowest band (R_m-*factor* → 0).

In order to compare the observed and simulated yield we used the root mean squared error (RMSE) for each province as:

$$\mathrm{RMSE} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2} \quad (2)$$

where n is the number of observed yields in each province, O is the observed yield, and S is the simulated yield for each individual province. The crop yield was simulated at the subbasin level and further aggregated to provincial scale in order to better match the provincial scale of the evaluation.

We also assigned a relative error of 10% to the observed statistical yield data, which are usually prone to errors due to constraints in surveys, reporting yield at different moisture contents, or estimating yields under different productivity levels (FAO, 2002; Bessembinder et al., 2005; Mo et al., 2005).

Table 3
The selected sensitive parameters in the calibration process.

Name	Definition	*t*-Value[a]	*p*-Value[b]
CN2.mgt	SCS runoff curve number for moisture condition II	19.801	2×10^{-16}
HI.mgt	Harvest index	18.519	2×10^{-16}
HEAT-UNITS.mgt	Crop required heat units	11.349	2×10^{-16}
SOL_AWC.sol	Soil available water storage capacity (mm H_2O/mm soil)	8.841	2×10^{-16}

[a] *t*-Value indicates parameter sensitivity. The large the *t*-value, the more sensitive the parameter.
[b] *p*-Value indicates the significance of the *t*-value. The smaller the *p*-values, the less chance of a parameter being accidentally assigned as sensitive.

3. Results and discussion

3.1. Model results

Table 1 summarizes the result of calibration and uncertainty analysis for different provinces for rainfed and irrigated wheat. The 95PPU simulated by SUFI-2 contains all sources of uncertainty (e.g., parameter input, conceptual model, and measured data) (Abbaspour et al., 2007). The *P-factor* (maximum value 1) depicts how well the calibration accounts for various uncertainties in the model. We obtained values that range between 0.77 and 1.0 for rainfed and from 0.70 to 1.0 for irrigated wheat. The R_m*-factor* (minimum value 0) depicts the strength of calibration. A smaller value indicates a smaller 95PPU band and closer simulated and observed values. In this study, R_m*-factor* generally ranged between 0.33 and 1.1 for rainfed and from 0.12 to 1.1 for irrigated wheat for most provinces. Overall, these statistics indicate quite good simulation results for wheat yield with relatively small uncertainties.

There are still some provinces for which simulation did not give good results, such as rainfed wheat in Ghom (Table 1), with a large R_m*-factor* of 1.51 (large uncertainty band). A large R_m*-factor* (>1) for some provinces indicates a large model uncertainty. It could mean that not all processes that are important in crop simulation are accounted for in the model. Some possible examples of conceptual model error could be different management practices, e.g., tillage operation, rotation, water harvesting, supplemental irrigation in rainfed farming, which are being used in Iran to increase crop yield. In addition, crop yield is sensitive to planting date as well as other factors. For example, the information provided by the Iranian Ministry of Agriculture for planting date in the Khozestan Province is: planting date from the first of November to the 20th of December. In this study, we used 20th of November as a fixed date for planting in Khozestan.

Table 2 shows a list of parameter uncertainty ranges in the first and the last iteration of SUFI-2 for rainfed and irrigated wheat. The final parameter ranges are much smaller than the initial values indicating the significance of the calibrating data in reducing the uncertainty. In Table 3 sensitivity of parameters important to crop yield is shown. All these four parameters are statistically very significant with *CN2* and *HI* being the most sensitive.

In Fig. 3, some examples of calibration and validation results are illustrated for individual provinces. Golestan and Gilan with larger rainfed yield in the country and Bushehr and Sistan Baluchestan with larger annual variability of rainfed wheat were chosen to illustrate the performance of the model both temporally and spatially. The calibration and validation results for irrigated wheat are shown for Khorasan-South and Yazd provinces to highlight the point that in these dry areas, irrigated wheat yield is close to or more than the country's average yield (3 ton ha^{-1}). Fig. 4 shows the modeled crop yield expressed as 95PPU intervals for all 30 provinces of the country for both rainfed and irrigated conditions. Also shown in the figure is the observed average annual (1990–2002) yield results, which are all within the predicted uncertainty band.

3.2. Quantification of CWP

In the next step, we used the calibrated model to calculate *CWP*. As yield and *ET* are closely related, calibration of yield increases our confidence on *ET* as well. To test the simulated *ET* against available data, we aggregated the modeled *ET* to provincial level and compared it with the available data from MOJA (Farshi et al., 1997) (Fig. 5). The simulated *ET* was further broken down based on its sources, i.e., rain (also referred to as consumptive green water use,

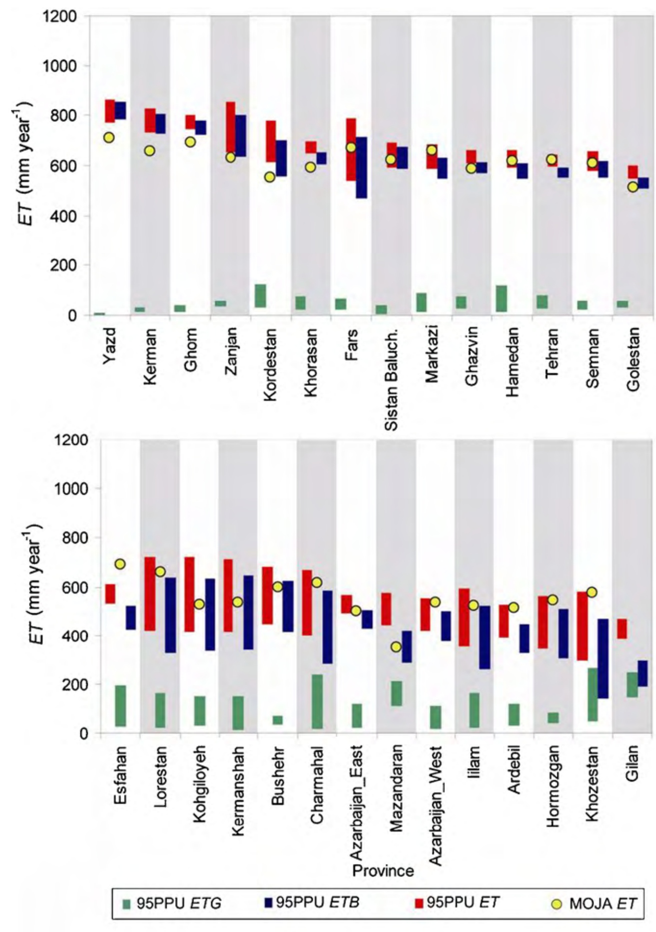

Fig. 5. Modeled average annual (1990–2002) consumptive water use (*ET*) expressed as 95%prediction uncertainty band (95PPU), and data obtained from the Ministry of Jahade-Agriculture (MOJA). The modeled data is further divided into precipitation-based (green water) (*ETG*) or irrigation-based (blue water) *ET* (*ETB*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

ETG) and irrigation (also referred to as consumptive blue water use, *ETB*). To calculate the contribution of rain alone to *ET* in irrigated areas, we ran the model first without considering irrigation. In Fig. 5, the MOJA values (total *ET*) are within or very close to the simulated 95PPU *ET*, which is shown as red bars. Blue and green bars show, respectively, the contribution from irrigation and pre-

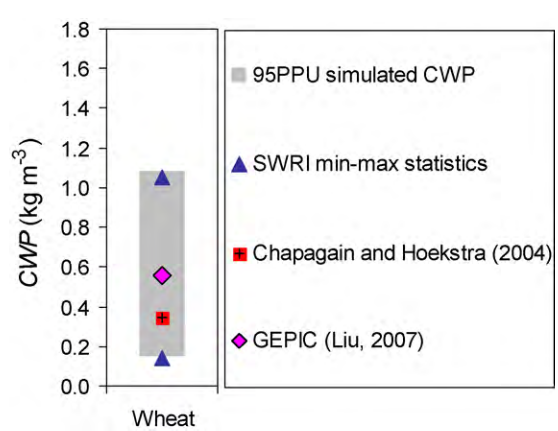

Fig. 6. Average annual (1990–2002) 95PPU of modeled *CWP* at national level and a comparison with the data reported by other sources.

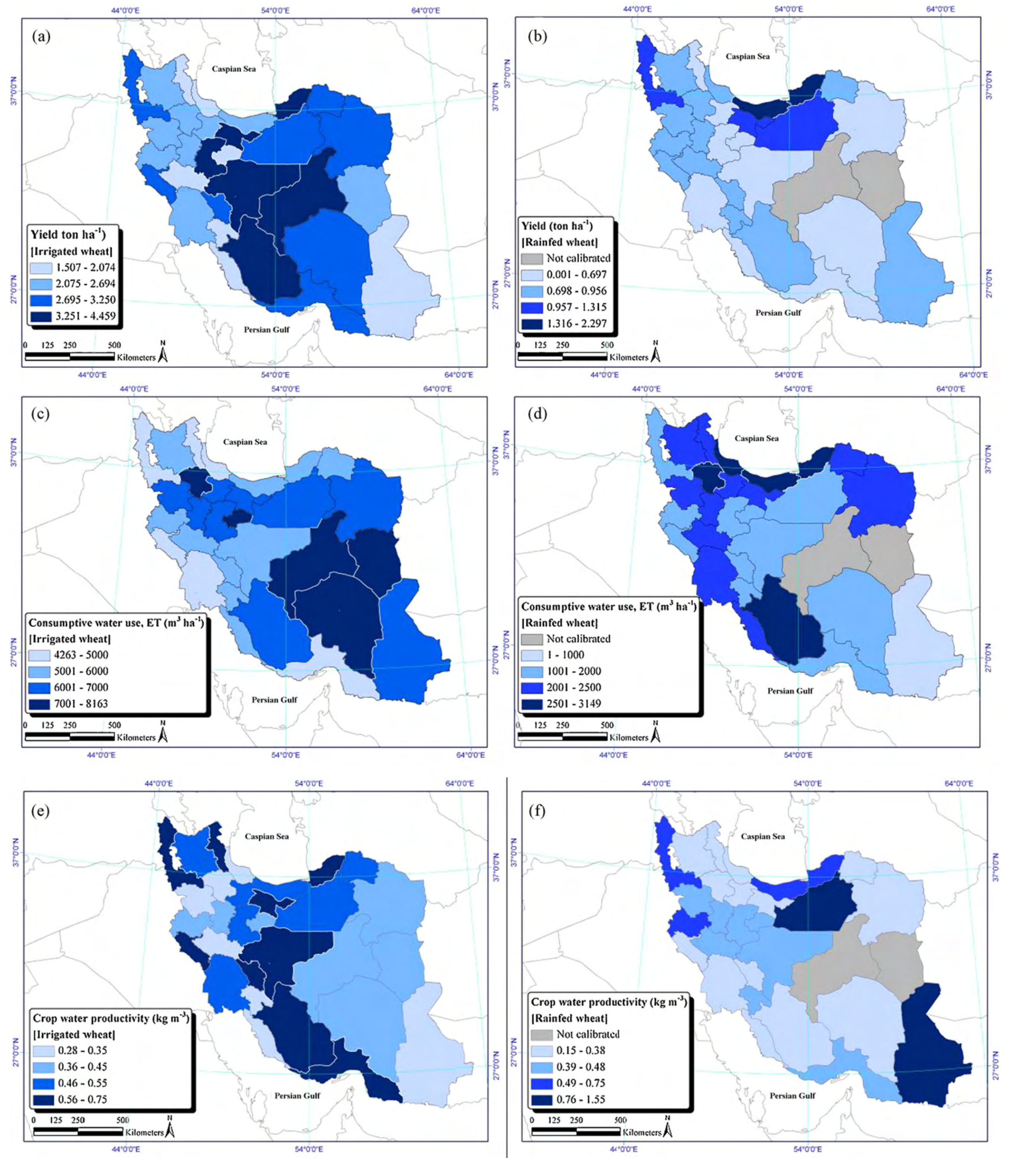

Fig. 7. The predicted average annual (1990–2002) yield, consumptive water use, and crop water productivity of rainfed (right) and irrigated (left) wheat for different provinces.

cipitation. Some of the discrepancies in this comparison could be explained by the fact that we used the Hargreaves method to calculate ET, whereas MOJA used the Penman-Monteith method (Farshi et al., 1997). Also, the agronomic practices (i.e., planting and harvesting dates and total fertilizer use) used in this study are based on the average long-term provincial data, while the number and dates of applications are based on the SWAT's automatic option, whereas MOJA used finer resolution sub-provincial information to calculate *ET*. Overall, the comparisons of the modeled and observed yield as well as modeled and previously estimated *ET* indicate that we have a good model of yield as well as hydrology.

As *CWP* has not been calculated before at the subbasin level and monthly time interval in Iran, we aggregated the results to annual and country level in order to compare it to some existing values. Fig. 6 compares the national predicted 95PPU of *CWP* (averaged over 1990–2002) with the values published in different sources. The country's average *CWP* estimated by Liu et al. (2007b), Chapagain and Hoekstra (2004), and the min-max values reported by the Soil and Water Research Institute (SWRI) of Iran (Banaei et al., 2005) are all within or close to our predicted uncertainty band. The estimates by Chapagain and Hoekstra (2004) are based on climate data on a representative site in a county, and that of Liu et al. (2007b) are based on a continuous-time series, grid based model with a spatial resolution of 30′. The *CWP* values reported by SWRI are roughly the average long-term minimum and the average long-term maximum *CWP* values observed at the country level. A direct one-to-one comparison of these values is not possible because they use different time periods and study-specific assumptions. The reason for showing this comparison is to give an overview of the differences in the existing numbers that are used in previous studies. The variation in different estimates indicates the uncertainty associated in such calculations, which is captured almost entirely in our prediction uncertainty as shown in Fig. 6.

As a general note on the usually large predicted model uncertainty, it could be argued that "large uncertainty" is not equivalent to "unpredictability". But it has been shown (Reichert and Borsuk, 2005) that uncertainty in the difference of model predictions corresponding to different policies may be significantly smaller than the uncertainty in the predictions themselves. The shown uncertainty in Fig. 6 is convoluted showing an integration of all kinds of uncertainties, including natural variability. For a practical application, it is possible to decrease this uncertainty by accounting only for some selected uncertainty sources of interest.

The average annual (1990–2002) predicted *Y*, *ET* and *CWP* across provinces are mapped for rainfed and irrigated wheat in Fig. 7. For rainfed wheat, *Y* and *CWP* correlate well, large yields correspond to large *CWP*, and vice versa. It is seen in Fig. 7f that in some Southern and Northern provinces the rainfed *CWP* is large. However, the contributions of *Y* and *ET* in these provinces are quite different. A small *Y* and a small *ET* could result in a large *CWP* in Southern areas, while a large crop yield, which needs less water, also produces a large *CWP* in Northern provinces. A comparison of the irrigated (left column) and rainfed (right column) maps in Fig. 7 illustrates that a large irrigated yield is achieved in some provinces where rainfed yield is small. But this does not provide a larger *CWP* than rainfed wheat as the *ET* in these areas is larger than rainfed wheat. Hence, to assess the productive potentials of a region, both *CWP* and yield must be considered together.

To show the temporal variability of *CWP*, we constructed the box-plots in Fig. 8. Overall, the variability of *CWP* is larger for rainfed wheat (from 0.15 to 1.55 kg m^{-3}) than irrigated wheat (from 0.28 to 0.75 kg m^{-3}) between the provinces. But as it is shown in Fig. 8a, in rainfed provinces, this variability is quite small for provinces with small *CWP* values and large across and within the provinces with

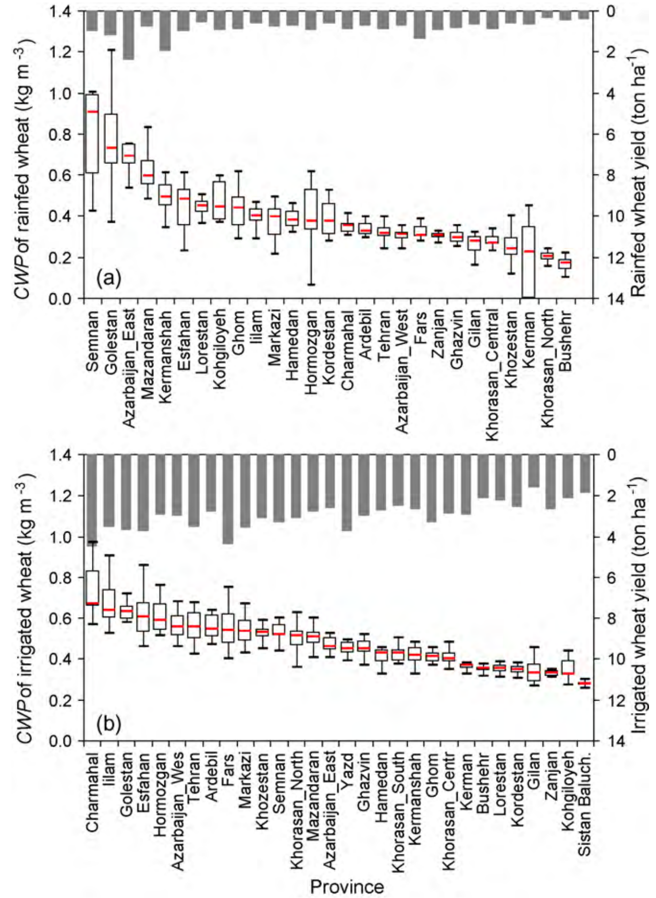

Fig. 8. Simulated rainfed and irrigated wheat *CWP* of different provinces. The annual (1990–2002) values are used to show the dispersion and skewness in the box-plots for each province.

larger *CWP*. Under irrigation conditions (Fig. 8b) the variability is significantly smaller. This is expected, as the production of irrigated wheat is rather consistent due to a more controlled agricultural condition across all the provinces.

3.3. Yield–ET–CWP relations

The relationship between wheat yield and *ET* is shown in Fig. 9a. Data points of all provinces from 1990–2002 for both irrigated and rainfed wheat were used in this illustration. The modeled wheat yields varied from 1.24 ton ha^{-1} to 6.2 ton ha^{-1} with an average

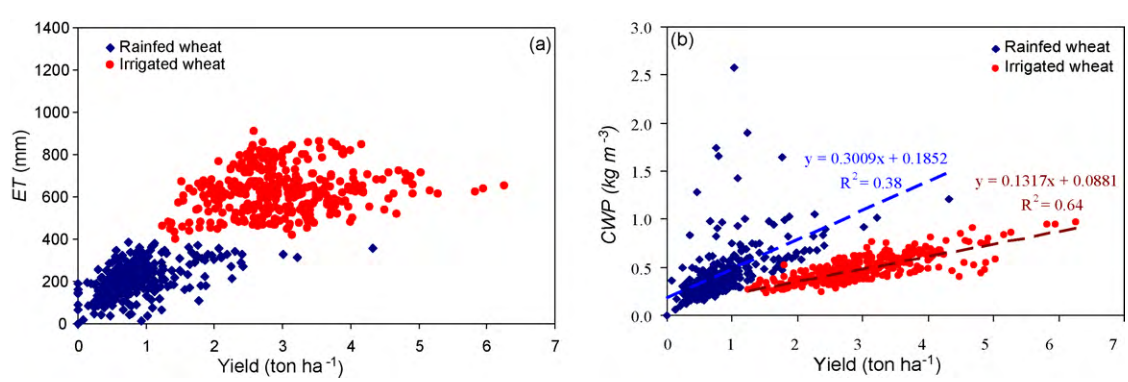

Fig. 9. *Y-ET* and *CWP-Y* relationships for (a) rainfed and (b) irrigated wheat. Data are from all provinces.

Table 4
Wheat yield (*Y*) and crop water productivity (*CWP*) of rainfed production and percent increases due to irrigation in different provinces.

Province	Rainfed *Y* (ton ha^{-1})	Rainfed *CWP* (kg m^{-3})	Irrigated *Y* increase as % of rainfed *Y*	Irrigated *CWP* increase as % of rainfed *CWP*
Khorasan_North	**0.43**	**0.20**	**608**	**155**
Bushehr	**0.36**	**0.15**	**477**	**138**
Khozestan	**0.63**	**0.25**	**386**	**112**
Charmahal	**0.67**	**0.36**	**561**	**108**
Iilam	**0.74**	**0.38**	**373**	**79**
Tehran	**0.67**	**0.32**	**420**	**77**
Fars	**0.93**	**0.32**	**367**	**76**
Kerman	**0.34**	**0.21**	**757**	**72**
Ardebil	**0.84**	**0.34**	**227**	**65**
Azarbaijan_East	**0.77**	**0.31**	**234**	**55**
Ghazvin	**0.62**	**0.30**	**375**	**53**
Hormozgan	0.59	0.41	392	50
Khorasan_Central	0.59	0.28	377	47
Markazi	0.71	0.39	402	41
Esfahan	0.53	0.47	593	33
Gilan	0.86	0.26	80	32
Hamedan	0.92	0.39	192	7
Zanjan	0.78	0.31	239	6
Ghom	0.61	0.43	432	−6
Kordestan	0.86	0.39	194	−11
Golestan	2.34	0.75	57	−16
Kermanshah	0.99	0.50	168	−16
Mazandaran	1.94	0.61	40	−17
Lorestan	0.90	0.43	143	−18
Azarbaijan_West	1.35	0.71	119	−21
Kohiloyeh	0.87	0.47	142	−25
Semnan	1.20	0.93	175	−43
Sistan Baluchestan	0.97	1.55	89	−82

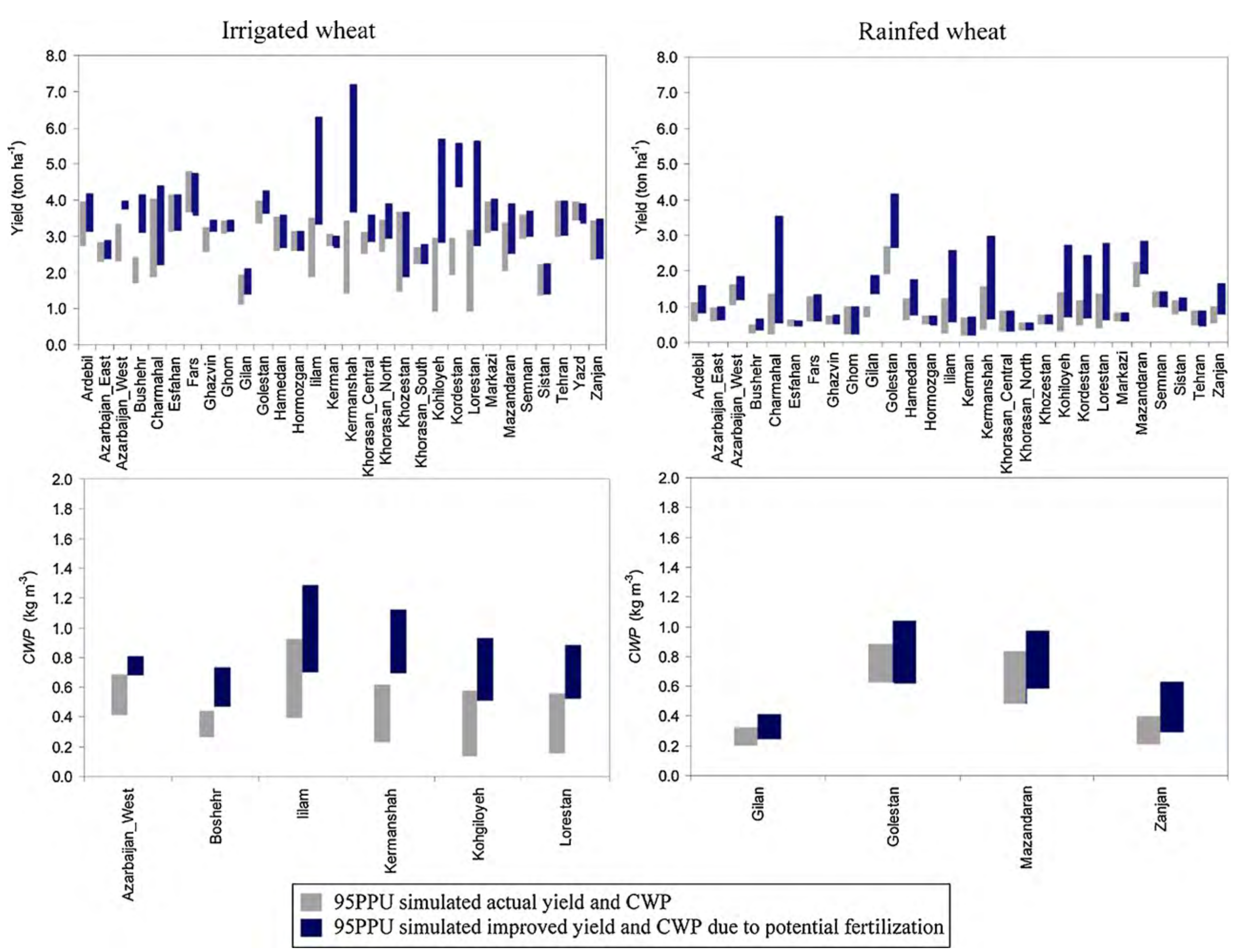

Fig. 10. Scenario analysis for potential fertilizer use. 95PPU of average annual (1990–2002) wheat yield, and *CWP* under irrigated and rainfed conditions for actual (historical) and potential fertilizer use scenarios.

Table 5
Province-based wheat production indicating actual average annual wheat in (1990–2002) period as well as the lower and upper limits of 95% uncertainty bands for production under potential fertilizer use scenarios. The table includes only the provinces that benefit from production increase with more fertilizer application.

Irrigated wheat (million ton year^{-1})				Rainfed wheat (million ton year^{-1})			
Province	Average production (AP)[a]	Lower 95PPU (IP)[b]	Upper 95PPU (IP)	Province	Average production (AP)	Lower 95PPU (IP)	Upper 95PPU (IP)
Azarbaijan_West	0.293	0.388	0.415	Gilan	0.017	0.026	0.037
Bushehr	0.022	0.034	0.045	Golestan	0.431	0.494	0.779
Iilam	0.047	0.059	0.112	Mazandaran	0.118	0.119	0.177
Kermanshah	0.123	0.185	0.368	Zanjan	0.232	0.233	0.512
Kohiloyeh	0.034	0.050	0.102				
Lorestan	0.182	0.243	0.507				

[a] AP is the actual production.
[b] IP is the improved production and 95PPU is the 95% prediction uncertainty.

of 3 ton ha^{-1} for irrigated land (shown in red dots), and from 0 to 4.32 ton ha^{-1} with an average of 0.91 ton ha^{-1} for rainfed land (shown in blue dots). The variation of *ET* was from 399 mm to 910 mm for irrigated wheat and from 0 to 386 mm for rainfed wheat, although physically there may be no yield at all for *ET* of less than 200 mm. Fig. 9b shows *CWP* of wheat against yield for the period of 1990–2002 for all provinces. There is a positive relationship between *Y* and *CWP* for both rainfed and irrigated wheat. In the rainfed wheat, there is a sharper increase in *CWP* in response to increasing yield as compared to irrigated wheat. This suggests that a unit increase in water results in a larger additional yield in rainfed than irrigated wheat, leading to a greater improvement in *CWP*. The results suggest that rainfed yield is more responsive to additional water. However, smaller R^2 in rainfed wheat (Fig. 9b) implies that this conclusion might not be the case for all provinces but rather circumstantial. The inference is that in some provinces a better water management in rainfed wheat, where yield is currently small, will lead to larger marginal return in the consumed water. This result is in agreement with the study by Rockstrom et al. (2007), where they found that for the smaller yield range; lesser incremental water is required to increase a unit of crop yield. In the smaller yield range, a vapor shift (transfer) from nonproductive evaporation (*E*) in favor of productive transpiration (*T*) will result in an improvement in *CWP*. In view of this situation, a shift from blue to green water management, as suggested by Falkenmark (2007) may be a way of dealing with water scarcity.

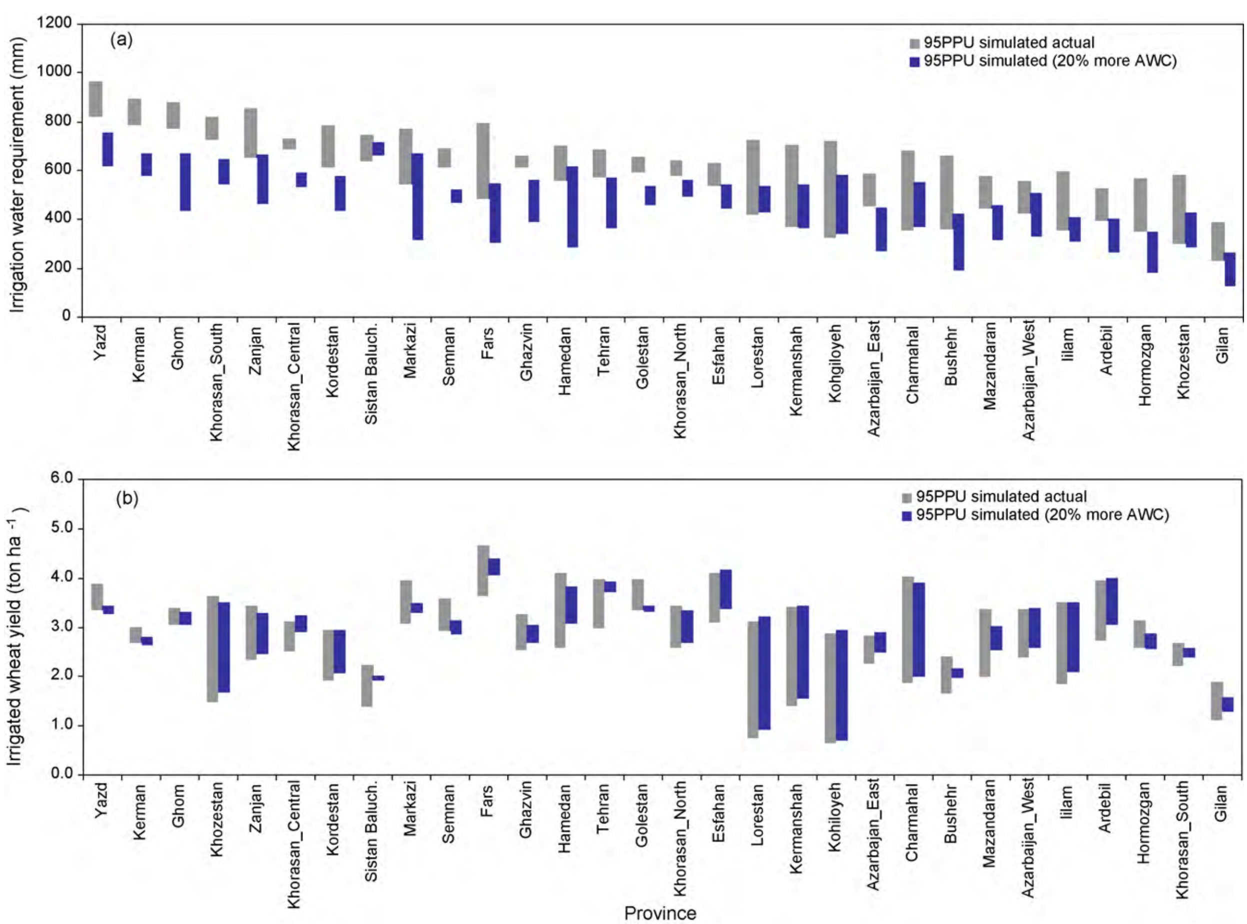

Fig. 11. Scenario analysis for increased available water capacity (*AWC*). (a) 95PPU of irrigation requirement, and (b) average annual (1990–2002) wheat yield under actual (historical) and 20% more *AWC* scenarios.

Table 6
Scenario analysis for assessment of water-use sustainability. In the last two columns we also added information on the scenario for sustaining self-sufficiency in wheat production for the year 2020. The last column shows how much extra water is needed in 2020 in terms of irrigation-based *ET* (*ETB*) to meet the wheat demand of an increasing population. Bold-underlined values highlight the situation in some strategic provinces with water scarcity or severe water scarcity.

Province	*IRWR*[a] (km^3)	Based on total of 18 major crops				Based on wheat only	
		IWR[b] (km^3)	*ETB*[c] (km^3)	*IWR/IRWR*	*ETB/IRWR*	*ETB*[c] (km^3)	*ETB*[c] (km^3) UN-medium scenario for 2020
Iilam	3.929	0.343	0.137	0.087	0.035	0.078	0.085
Kohgiloyeh	4.843	0.570	0.228	0.118	0.047	0.099	0.106
Kordestan	5.951	0.792	0.317	0.133	0.053	0.236	0.276
Charmahal	5.296	0.712	0.285	0.135	0.054	0.164	0.178
Kermanshah	4.974	1.201	0.480	0.241	0.097	0.284	0.307
Lorestan	6.026	2.120	0.848	0.352	0.141	0.486	0.527
Gilan	9.723	3.478	1.391	0.358	0.143	0.002	0.003
Bushehr	2.339	1.110	0.444	0.475	0.190	0.060	0.070
Fars	20.545	10.283	4.113	0.501	0.200	1.971	2.292
Hormozgan	4.797	2.635	1.054	0.549	0.220	0.044	0.051
Azarbaijan_West	4.240	2.613	1.045	0.616	0.247	0.490	0.555
Ghazvin	1.827	1.130	0.452	0.618	0.247	0.379	**0.456**
Khozestan	10.898	8.186	3.275	0.751	0.300	0.888	0.969
Esfahan	6.210	4.883	1.953	0.786	0.315	0.493	**0.584**
Mazandaran	5.006	4.732	1.893	0.945	0.378	0.012	0.013
Ardebil	1.384	1.346	0.538	0.973	0.389	0.269	0.308
Zanjan	1.345	1.777	0.711	1.322	0.529	0.320	**0.486**
Sistan Bluch.	1.991	2.768	1.107	1.391	0.556	0.515	**0.616**
Tehran	1.369	1.965	0.786	1.435	0.574	0.364	**0.440**
Kerman	4.944	7.179	2.872	1.452	0.581	0.871	**1.041**
Hamedan	1.372	2.210	0.884	1.611	0.644	0.552	**0.662**
Yazd	0.508	0.877	0.351	1.727	0.691	0.168	**0.199**
Semnan	0.564	1.080	0.432	1.916	0.766	0.201	**0.242**
Khorasan	5.329	10.387	4.155	1.949	0.780	2.227	**2.681**
Golestan	0.794	2.205	0.882	2.777	1.111	0.400	0.481
Azarbaijan_East	1.066	3.302	1.321	3.099	1.240	0.676	**0.801**
Markazi	0.464	2.217	0.887	4.776	1.910	0.520	**0.620**
Ghom	0.057	0.489	0.196	8.654	3.462	0.113	**0.135**

[a] *IRWR* is internal renewable water resource.
[b] *IWR* is irrigation water requirement including irrigation inefficiencies.
[c] *ETB* is irrigation-based *ET*.

4. Assessing some policy implications

In the National Research Council's report (NRC, 2005), objectives and highlights of the agricultural program in the Third Five-Year Development Plan (2001–2005) included: improving quantity of agricultural products with priorities given to cereals, implementing policies to increase yields through efficient use of land and water resources, improving activities related to soil moisture conservation and retention, and innovative approaches to optimize the use of irrigation and fertilizer application (Keshavarz et al., 2005). In the following we show how our model could be used to assess the implications of these strategies.

4.1. Assessment of irrigation application

To observe more clearly the *Y-CWP* relation for rainfed and irrigated wheat in individual provinces, we constructed Table 4. This table shows the potential improvement in yield and *CWP* when shifting from rainfed to irrigated conditions. In this analysis water availability or sustainability was not addressed. It is seen that in all provinces wheat yield increases with the shift. *CWP* of the first 11 provinces (highlighted with bold font) increases substantially (>50%). In the middle 7 provinces (highlighted with underline), *CWP* increases in the range of 0–50%. The last group of the provinces shows a decrease in *CWP* with increasing irrigation. Considering that the average rainfed wheat yield for the three groups are 0.63, 0.73 and 1.2 ton ha^{-1}, respectively, we conclude that the provinces with smaller yield could increase their *CWP* more effectively as yield is improved by irrigation. In provinces in the last group, where *CWP* decreases by introducing irrigation, a large incremental *ET* is required to achieve a unit of increase in yield. The reason could be quite different for different provinces. For example in Ghom, located in a dry region at the center of the country, increasing wheat yield from about 0.61 ton ha^{-1} (small yield under rainfed condition) to more than 3.2 ton ha^{-1} (large yield under irrigated condition) does not significantly change *CWP* as a proportional increase in *ET* is required. On the other hand, in Sistan Baluchestan, a dry region in the south east of the country, a small increase in yield requires a large increase in *ET*, resulting in a sharp decrease in *CWP*. This might be due to the dry climatic conditions where evaporative demand is very large. But in the same group there is Mazandaran, a humid region in the north of Iran, where irrigation does not improve the yield significantly. This province does not have water limitation, but rather limitation is most likely due to temperature. A case by case study of the provinces is, therefore, required for a deeper understanding of the *Y-ET-CWP* relationship.

4.2. Assessment of fertilizer application

Fertilizer application has been one of the major ways to increase crop yield in Iran in the last decade. To assess yield changes with increasing fertilization we used an option in the SWAT program that applies unrestricted fertilizer as required. Fig. 10 illustrates the resulting changes in yield in all provinces, as well as the changes in *CWP* in provinces where crop yield increases as fertilizer constraint is relaxed for irrigated and rainfed wheat. It is found that in many provinces, actual yield (obtained by actual fertilizer use data) is equal to or very close to the improved yield (obtained by unrestricted fertilizer use in the model). But there are also some provinces where fertilizer seems to be a limiting factor to yield in both irrigated and rainfed productions for the period observed (1990–2002). For these provinces, *CWP* and production show increases as a result of a better fertilizer management. Table 5 lists six provinces with irrigated wheat and four provinces with rainfed wheat in the country, which have the potential to achieve a larger yield and *CWP* with unrestricted fertilizer supply. The improvement in *CWP* in these provinces is mostly due to the increase in yield with negligible change in *ET*. These provinces cover, respectively, 13% and 14% of the irrigated and rainfed wheat-cultivated-areas in the country. Using the average annual (1990–2002) simulated and improved wheat yield, we computed the crop production and expressed it as 95PPU in the respective provinces to account for model uncertainty. Provinces where historic average production is smaller or equal to the lower 95% uncertainty bond are highlighted as they are more certain to benefit from a better fertilizer management.

4.3. Assessment of improvements in soil water retention capacity

Soil management through improving soil fertility or available water capacity (*AWC*) has been considered as one of the priorities and future challenges on the enhancement of agricultural productivity in Iran (NRC, 2005). In many parts of the country, poor quality of soil is one of the major limiting factors in achieving optimum production. Proper soil management practices are usually urged by policy makers for sustainable agriculture. However, their impact on water use is usually not known. In this study we quantify the impact of improving *AWC* by 20% across the country on the irrigation water requirement. We used the calibrated model and ran it with increased soil water storage capacity while keeping other parameters unchanged. The results in Fig. 11 show that in most provinces, less irrigation water is required to satisfy the water demand in the root zone to achieve the same amount of wheat yield. A simple calculation shows that around 1.54–2.07 km^3 of irrigation water could be saved annually, which is about 5–6% of the total historic irrigation water use for wheat.

4.4. Assessment of water-use sustainability

An increasing competition in water use due to population growth, economic development, and a decreasing trend in water resources availability give urgency to balancing water supply and demand in Iran. Fig. 12a illustrates the ratio of irrigation water requirement (*IWR*) (data of all crops from Farshi et al. (1997) except wheat and barley, which was calculated in this study) to the internal renewable blue water availability (*IRWR*) (data from Faramarzi et al., 2009) for 18 main crops across the provinces. In 21 provinces this ratio is more than 40% (Table 6). These provinces are "water scarce" according to an index developed by Raskin et al. (1997) and Alcamo et al. (2007). In 12 provinces (indicated by red color in the figure) the ratio is more than 100%. This is an indication of "severe water scarcity" and groundwater resource depletion. It is estimated that with the current rate of over extraction and climate change induced droughts, groundwaters will be exhausted within the next 50 years in these provinces (Abbaspour et al., 2009; Mousavi, 2005; Pazira and Sadeghzadeh, 1999). Therefore, water scarcity is becoming a major limiting factor in the sustainability of the future irrigated agricultural production and specially wheat production in most provinces of the country. The above calculation of *IWR* is based on an assumption that 60% of the water is lost due to irrigation and conveyance inefficiency (Dehghani et al., 1999). To see what would happen if this inefficiency was to be corrected, we plotted Fig. 12b based on the consumptive blue water use (*ETB*), which does not include any water losses. It is seen that still 12 provinces have the ratio of *ETB* to blue water availability over 40% and four provinces have the ratio of over 100%. Table 6 quantifies

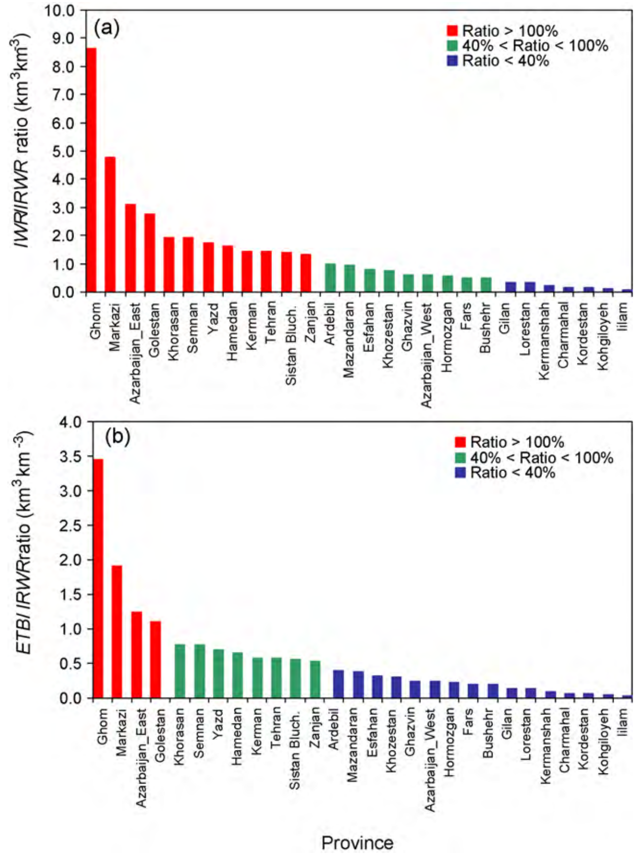

Fig. 12. Ratio of provincial irrigation-based *ET* (*ETB*) and provincial irrigation water requirement (*IWR*) to water availability (expressed as internal renewable water resources, *IRWR*) based on the average of (1990–2002) data. Data for provincial *ETB* and *IWR* are calculated for 18 main crops across the provinces.

in detail provincial *IRWR*, *IWR*, *ETB*, and the water scarcity ratios for all provinces.

As already mentioned, wheat is the core commodity of the country where its cultivation has been emphasized over the last decades. After 45 years of importing the commodity, Iran announced in November 2004 that it was self-sufficient in wheat production (Deihimfard et al., 2007). It produced 14 million tons of wheat, of which, 67% was from irrigated land and 33% from rainfed land (SCI). It is widely believed that the country cannot sustain this level of wheat self-sufficiency in the future due to water scarcity. To test this hypothesis, we calculated the *ETB* required for irrigated wheat for the year 2020 and compared it with the year 2004. For this analysis, we obtained large variant, medium variant, and small variant population scenarios from the United Nation's population prediction (http://esa.un.org/unpp/index.asp), and kept other factors as they were in 2004 including the per capita production and per capita *ETB* distribution. Also, to estimate the provincial production for the year 2020, we distributed the national production based on the percentage of their contribution to the country's wheat production. This ratio was obtained by using the provincial based historical irrigated wheat production. The last two columns of Table 6 show the water needed to fully meet the expected demand in 2020 without wheat import. In the last column, some provinces are highlighted where consumptive blue water demand for wheat is significantly larger than what was required in the past.

Fig. 13 shows the provincial *ETB* for the three UN population scenarios. It is seen that in 13 provinces the average *ETB* in the year 2020 are significantly higher than the average *ETB* of the year 2004, i.e., a substantial increase in water demand. We calculated that 88% of the increase in production comes from the provinces

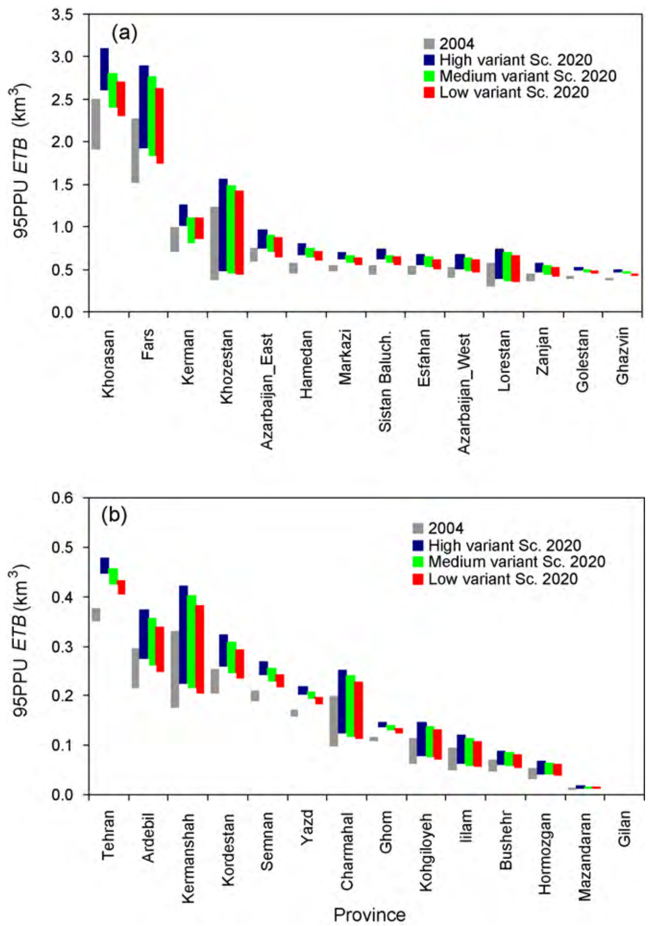

Fig. 13. Scenario analysis for water demand for irrigated wheat to maintain self-sufficiency in 2020. The medium variant population scenario shows a significant increase in water requirement in all provinces.

that already have water scarcity ratio above 40% (e.g., Ghom, Semnan, Yazd, Sistan, Tehran, Ghazvin, Kerman, Khorasan, Esfahan, and Markazi). At the national level, the required *ETB* for wheat was found to be 11–14 km^3 year^{-1} for the year 2004. This requirement for the year 2020 was calculated to be around 12–16, 13–17, and 14–18 km^3 year^{-1} for the three UN low, median, and high scenarios, respectively. Therefore we could expect that the above provinces to face serious water shortages, threatening the long-term food security of the country. The situation becomes even more critical if we take into consideration the poor water resources management and low irrigation inefficiency in Iran as well as the predicted ensuing droughts due to climate change (Abbaspour et al., 2009). Therefore, the question of where the needed water will come from, urges a serious consideration of the agricultural production strategy in Iran.

5. Conclusion

The SWAT model was used to simulate the processes related to soil-crop-atmosphere interaction. Calibration and validation were performed using the SUFI-2 program in SWAT-CUP package. It was important to quantify uncertainty as the model was subject to different sources of uncertainties including conceptual model uncertainty, input data, and parameter uncertainties for yield and *CWP*. The unrealisticly large values in the prediction of uncertainty for HI_{ac} in some provinces might be due to the influence of other parameters on crop yield, which have not been considered in the calibration process but are reflected by HI_{ac}.

In the analysis of *Y-CWP* relationship we conclude that a better water management in rainfed wheat, where yield is currently small, will lead to a larger marginal return in the consumed water. In many provinces (Table 4) shifting from rainfed wheat to irrigated wheat can lead to an increase in *CWP*. However, the trend is the opposite in the provinces located in the arid part of the country due to a high evaporative demand.

An improved *Y* due to unrestricted fertilizer application in the model showed that in many provinces, the improvement was marginal indicating that fertilizer is adequately used in these provinces. The results showed that in six provinces with irrigated wheat and four provinces with rainfed wheat in the country, there is potential to achieve a larger yield and *CWP* with unrestricted fertilizer supply.

An assessment of improvement in soil available water capacity (*AWC*) showed an improvement in irrigation water use. The results showed that 18 out of 30 provinces are more certain to save water while increasing *AWC* trough proper soil management practices. Taking the average 95PPU of the modeled irrigation in the improved *AWC* scenario, we calculated that 1.54–2.07 km^3 of irrigation water will be saved annually if *AWC* is increased by 20%.

In a further analysis we found that there was a miss-match between the water availability and water use in many provinces of the country (Table 6). The analysis revealed that only 7 out of 30 provinces have the ratio of water use to water availability less than 40%. This means that 23 provinces are subject to some degree of water scarcity. The ratio is even more than 100% in 12 provinces.

An analysis of future water demand to meet the self-sufficiency of wheat revealed that there is not enough water in most of the provinces to meet the required production in the year 2020. This would be so, even if attempts were made to save all the water that was lost due to irrigation inefficiency. The situation will become even more critical if considering the existing water use inefficiency in Iran as well as the predicted ensuing droughts due to climate change.

Finally, models always have conceptual short comings in simulation of actual processes. In this case, simulation of different crop stresses and their effect on each other are some conceptual short comings of SWAT. This is evident in Fig. 9 where crop yields are simulated with ET values of less than 200 mm. In reality, no crop will be produced at this water level. Other short comings in the crop yield simulation are as always related to the lack of information. Important to crop yield simulation are planting and harvest dates, dates of irrigation and pesticide applications, and also consideration of seed variety, which is usually missing from the analysis. As our analyses were performed in a large scale, some simplifying assumptions were, however, unavoidable.

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