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Modelling blue and green water resources availability in Iran

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Abstract:

Knowledge of the internal renewable water resources of a country is strategic information which is needed for long-term planning of a nation's water and food security, among many other needs. New modelling tools allow this quantification with high spatial and temporal resolution. In this study we used the program Soil and Water Assessment Tool (SWAT) in combination with the Sequential Uncertainty Fitting program (SUFI-2) to calibrate and validate a hydrologic model of Iran based on river discharges and wheat yield, taking into consideration dam operations and irrigation practices. Uncertainty analyses were also performed to assess the model performance. The results were quite satisfactory for most of the rivers across the country. We quantified all components of the water balance including blue water flow (water yield plus deep aquifer recharge), green water flow (actual and potential evapotranspiration) and green water storage (soil moisture) at sub-basin level with monthly time-steps. The spatially aggregated water resources and simulated yield compared well with the existing data. The study period was 1990–2002 for calibration and 1980–1989 for validation. The results show that irrigation practices have a significant impact on the water balances of the provinces with irrigated agriculture. Concerning the staple food crop in the country, 55% of irrigated wheat and 57% of rain-fed wheat are produced every year in water-scarce regions. The vulnerable situation of water resources availability has serious implications for the country's food security, and the looming impact of climate change could only worsen the situation. This study provides a strong basis for further studies concerning the water and food security and the water resources management strategies in the country and a unified approach for the analysis of blue and green water in other arid and semi-arid countries.

KEY WORDS internal water resources availability; irrigated wheat yield; large-scale hydrologic modelling; SWAT; SUFI-2; uncertainty analysis

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INTRODUCTION

There are many studies concerning the increasing threat of water scarcity and vulnerability of water resources at regional and global scales (Postel *et al*., 1996; Cosgrove and Rijsberman, 2000; Vörösmarty *et al*., 2000; Oki and Kanae, 2006). As the agricultural sector is by far the largest water user, the main focus of most water scarcity studies is on the impact on agricultural and food security. Measures have been sought to produce more food with less water by increasing crop water productivity through effective development of genotypes and development of new technologies for integrated crop management (Kijne *et al*., 2003; Bouman, 2007).

Another way of dealing with water scarcity is through the use of 'virtual water trade strategy' (Allan, 1997). At the global level, Yang *et al*. (2006) show that water saving results from virtual water trade because major flow of virtual water is from countries with large crop water productivity to countries with small crop water productivity. Within a country, virtual water trade can also result in water saving and water use efficiency at watershed and national levels. According to this concept, water-scarce regions can use their water resources more efficiently by a combination of innovative local agricultural production (e.g. greenhouse and hydroponic production) and import from outside what they need to meet the local food demand. The import from outside can be thought of as 'virtual water' entering the region to compensate the local water shortages. At the national level, food self-sufficiency has been a desired objective of the Iranian government; nevertheless, large amounts of food are imported into the country in drought years. This is partly due to the lack of water for expanding agricultural production. Wheat import during the drought years of 1999–2001 accounted for 80% of the country's total domestic wheat supply, making Iran one of the largest wheat importers of the world at the time (FAO, 2005).

Given the close relationship between water and food, a systematic assessment of water resources availability with high spatial and temporal resolution is essential in Iran for strategic decision-making on food security. Although initiatives have been taken to quantify water availability by the Ministry of Energy (MOE), the implementation has been slow and non-systematic so far. To our knowledge, the national water planning report by the MOE (1998) is the only available source, which provides water resources availability data in surface water and harvestable groundwater resources on a regional scale for Iran. There is, however, a lack of information with adequate spatial and temporal resolution concerning

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the hydrological components affecting the availability of water resources in the country.

Water resource development through the water transfer projects, construction of dams, weirs and levees and extraction of water for irrigation purposes can significantly alter the hydrology (Thoms and Sheldon, 2000). In arid and semi-arid countries such as Iran, due to the low rate, high variability and uneven distribution of precipitation, water resources in aquifers and rivers are subject to high levels of exploitation and diversion from their natural conditions (Abrishamchi and Tajrishi, 2005). Accounting for these man-made changes in water courses presents a formidable challenge in hydrological modelling. Irrigated agriculture, which uses more than 90% of total water withdrawal and more than 60% of total renewable water resources in the country (Alizadeh and Keshavarz, 2005; Keshavarz *et al.*, 2005), has a major effect on the hydrological water balance. Therefore, incorporating water management practices (e.g. water storage by dams and irrigation in agriculture) is essential in obtaining more precise and realistic information on water resources availability in individual watersheds and in the country as a whole.

Against this background, the main objective of this study is first to calibrate and validate a hydrologic model of Iran at the sub-basin level with uncertainty analysis. The second objective is to estimate water resources availability at the sub-basin level on a monthly time-step considering the impact of water resources management practices in the country. Third, we aim to explicitly quantify hydrological components of water resources, e.g. surface runoff and deep aquifer recharge (blue water flow), soil water (green water storage) and actual evapotranspiration (green water flow).

This work is intended to provide a basis for future scenario analysis of water resource management, virtual water trade and climate change in Iran. Model calibration and validation is based on river discharge data from 81 gauging stations and wheat yield data from irrigated regions. As crop yield is directly proportional to actual evapotranspiration (Jensen, 1968; FAO, 1986), model calibration using crop yield provides more confidence on the partitioning of water between soil storage, actual evapotranspiration and aquifer recharge than calibrations based on river discharge alone.

To satisfy the objectives of this study, the Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) was used to model the hydrology of Iran. SWAT is a continuous time and spatially distributed watershed model, in which components such as hydrology, crop growth related processes and agricultural management practices are considered.

SWAT was preferred to other models in this project for various reasons. For example, CropWat and CropSyst (Confalonieri and Bocchi, 2005) are only capable of simulating crop growth related processes. WaterGAP 2 (Alcamo *et al.*, 2003; Döll *et al.*, 2003) consists of two independent components for hydrology and water use, but does not include crop growth and agricultural management practices. GIS based Erosion Productivity Impact Calculator (GEPIC) (Liu *et al.*, 2007) addresses spatial variability of crop yield and evapotranspiration, but lacks an explicit component for large scale hydrology. Soil and Water Integrated Model (SWIM) (Krysanova *et al.*, 2005) was developed for use in mesoscale and large river basins (>100 000 km^2) mainly for climate change and land use change impact studies, and Simulation of Production and Utilization of Rangelands (SPUR) is an ecosystem simulation model developed mostly for rangeland hydrology and crops (Foy *et al.*, 1999).

For calibration and uncertainty analysis in this study, we used the Sequential Uncertainty Fitting program SUFI-2 (Abbaspour *et al.*, 2007). SUFI-2 is a tool for sensitivity analysis, multi-site calibration and uncertainty analysis. It is capable of analysing a large number of parameters and measured data from many gauging stations simultaneously. Yang *et al.* (2008) found that SUFI-2 needed the smallest number of model runs to achieve a similarly good calibration and prediction uncertainty results in comparison with four other techniques. This efficiency is of great importance when dealing with computationally intensive, complex large-scale models. In addition, SUFI-2 is linked to SWAT (in the SWAT-CUP software; Abbaspour, 2007) through an interface that also includes the programs Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Parameter Solution (ParaSol) (van Griensven and Meixner, 2006), and a Monte Carlo Markov Chain (MCMC) (Vrugt *et al.*, 2003) algorithm.

MATERIALS AND METHODS

The hydrologic simulator (SWAT)

SWAT is a computationally efficient simulator of hydrology and water quality at various scales. The program has been used in many international applications (Arnold and Allen, 1996; Narasimhan *et al.*, 2005; Gosain *et al.*, 2006; Abbaspour *et al.*, 2007; Yang *et al.*, 2007; Schuol *et al.*, 2008a, b). The model is developed to quantify the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land uses and management conditions over long periods of time. The main components of SWAT are hydrology, climate, nutrient cycling, soil temperature, sediment movement, crop growth, agricultural management and pesticide dynamics. In this study, we used Arc-SWAT (Olivera *et al.*, 2006), where ArcGIS (version 9·1) environment is used for project development.

Spatial parameterization of the SWAT model is performed by dividing the watershed into sub-basins based on topography. These are further subdivided into a series of hydrologic response units (HRU) based on unique soil and land use characteristics. The responses of each HRU in terms of water and nutrient transformations and losses are determined individually, aggregated at the sub-basin level and routed to the associated reach and catchment

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outlet through the channel network. SWAT represents the local water balance through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m). The soil water balance equation is the basis of hydrological modelling. The simulated processes include surface runoff, infiltration, evaporation, plant water uptake, lateral flow and percolation to shallow and deep aquifers. Surface runoff is estimated by a modified Soil Conservation Service (SCS) curve number equation using daily precipitation data based on soil hydrologic group, land use/land cover characteristics and antecedent soil moisture.

In this study, potential evapotranspiration (PET) was simulated using the Hargreaves method (Hargreaves *et al.*, 1985). Actual evapotranspiration (AET) was predicted based on the methodology developed by Ritchie (1972). The daily value of the leaf area index (LAI) was used to partition the PET into potential soil evaporation and potential plant transpiration. LAI and root development were simulated using the crop growth component of SWAT. This component represents the interrelation between vegetation and hydrologic balance. Plant growth was determined from leaf area development, light interception and conversion of intercepted light into biomass assuming a plant species-specific radiation use efficiency. Phenological plant development was based on daily accumulated heat units, potential biomass and harvest index. Harvest index is the fraction of above-ground plant dry biomass that is removed as dry economic yield to calculate crop yield. Plant growth, in the model, can be inhibited by temperature, water, nitrogen and phosphorus stress factors. A more detailed description of the model is given by Neitsch *et al.* (2002).

Description of the study area

Climate and hydrology. Iran, with an area of 1 648 000 km^2, is located between 25–40°N and 44–63 °E. The altitude varies from −40 m to 5670 m, which has a pronounced influence on the diversity of the climate. Although most parts of the country could be classified as arid and semi-arid, Iran has a wide spectrum of climatic conditions. The average annual precipitation is 252 mm yr^{-1}. The northern and high altitude areas found in the west receive about 1600–2000 mm yr^{-1} (NCCO 2003), while the central and eastern parts of the country receive less than 120 mm yr^{-1}. The per capita freshwater availability for the country was estimated at around 2000 m^3 capita^{-1} yr^{-1} in the year 2000 and expected to go below 1500 m^3 capita^{-1} yr^{-1} (the water scarcity threshold) by 2030 due to the population growth (Yang *et al.*, 2003). Winter temperatures of −20 °C and below in high-altitude regions of much of the country and summer temperatures of more than 50 °C in the southern regions have been recorded (NCCO, 2003).

According to the national water planning report by the MOE (1998), Iran can be divided into eight main hydrologic regions (HR) comprising a total of 37 river basins. We used the MOE hydrologic regions as the basis for comparison in our study. The eight main hydrologic

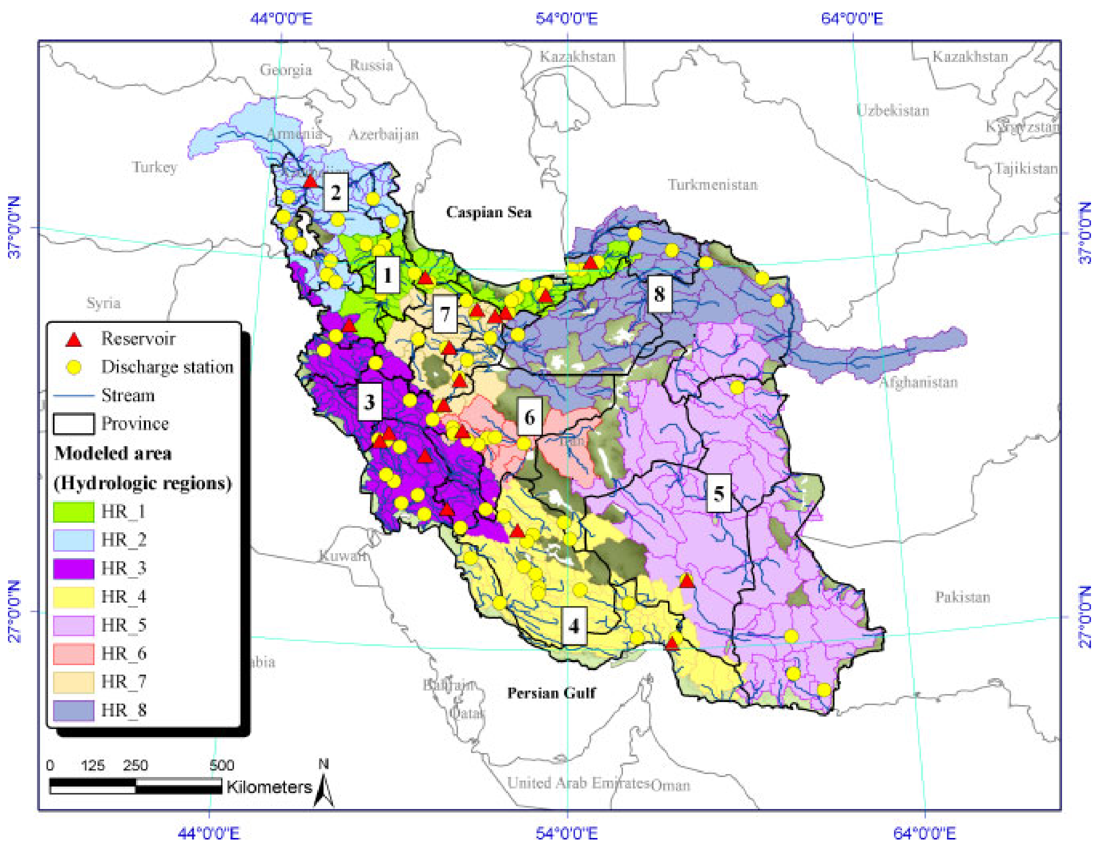

Figure 1. Study area and the main hydrologic regions. The dark green areas in the background include wetlands, lakes and marshes which needed to be cut from the DEM in order to have a correct river pattern (not included in the model)

Table I. Watershed characteristics of the eight main hydrologic regions in Iran

Hydrologic region	Area[a] (km^2)	Mean precipitation[b]	Number of sub-basins	% Land use[c]								
				BSVG	CRDY	CRGR	CRIR	CRWO	FODB	GRAS	SAVA	SHRB
HR 1	97 478	599	66	—	—	1·55	15·13	3·59	13·09	61·96	1·81	2·83
HR 2	131 973	399	58	—	14·20	—	—	11·30	—	54·22	17·53	2·61
HR 3	185 042	545	92	2·35	7·92	—	—	7·025	—	29·25	—	53·44
HR 4	196 329	278	87	25·27	—	—	—	1·77	—	1·77	—	71·18
HR 5	459 309	132	68	35·68	2·44	0·15	1·01	2·55	0·86	18·20	1·68	37·38
HR 6	66 654	152	26	65·28	—	0·13	0·40	—	—	7·08	—	27·08
HR 7	82 268	287	43	17·17	—	—	—	—	—	28·97	—	53·85
HR 8	256 553	197	67	27·48	0·99	—	—	1·08	—	18·21	—	52·22

[a] Modelled area: area of sub-basins delineated in each HR were aggregated
[b] Available from Ministry of Energy of Iran (1998) report
[c] Extracted from USGS land use database using SWAT selected dominant land use and soil for each sub-basin. BSVG: barren or sparsely vegetated; CRDY: dryland cropland pasture; CRGR: cropland-grassland mosaic; CRIR: irrigated cropland and pasture; CRWO: cropland-woodland mosaic; FODB: deciduous broadleaf forest; GRAS: grassland; SAVA: savanna; SHRB: shrub land.

Table II. Characteristics of 19 large reservoirs included in the SWAT model

Name	River	Year of completion	Longitude (degree)	Latitude (degree)	Surface area (km^2)	Gross capacity ($\times 10^6$ m^3)
Aras	Aras	1971	45·40	39·10	145	1350
Dez	Dez	1962	48·46	32·61	62.5	2600
Doroudzan	Kor	1973	52·49	30·16	55	993
Gheshlagh	Gheshlagh	1979	47·01	35·39	8.5	224
Golpayegan	Ghom Rud	1957	50·13	33·42	2.7	57
Gorgan	Gorgan Rud	1970	54·76	37·22	18.2	97
Jiroft	Halil Rud	1991	57·57	28·79	9.7	336
Karaj	Karaj	1961	51·09	35·95	3.9	205
Karkheh	Karkheh	2001	48·19	32·39	161	7300
Lar	Lar	1982	52·00	35·89	29	960
Latyan	Jaj Rud	1967	51·68	35·79	2.9	95
Maroun	Maroun	1999	50·34	30·68	25.1	1183
Minab	Minab	1983	57·06	27·15	18.2	344
Panzdah-khordad	Ghom Rud	1994	50·61	34·08	14.1	195
Saveh	Vafregan	1993	50·24	34·93	8.3	293
Sefid Rud	Sefid Rud	1962	49·38	36·75	46.4	1765
Shahid Abbaspour	Karun	1977	49·61	32·06	51.7	3139
Shahid Rajayee	Tajan	1998	53·30	36·35	4.1	191
Zayandeh Rud	Zayandeh Rud	1970	50·74	32·74	48	1450

regions are delineated in Figure 1. Table I shows some pertinent characteristics of the eight hydrologic regions. Table II provides a list of dams on the major rivers that were included in the model.

In HR1, Sefid Rud and Haraz are the main rivers. Sefid Rud is 670 km long, rises in northwest Iran and flows generally east to meet the Caspian Sea. It is Iran's second longest river after Karun. A storage dam on the river was completed in 1962. Haraz is a river in Northern Iran that flows northward from the foot of Mount Damavand to the Caspian Sea cutting through Alborz. A storage dam has been constructed on the Lar River which is an upstream tributary of the Haraz River. There are many other short rivers which originate from the Alborz Mountains and flow toward the Caspian Sea. This is a water-rich region.

In HR2, Lake Urmiyeh is a permanent salt lake receiving several permanent and ephemeral rivers. Aras is an international river. It originates in Turkey and flows along the Turkish–Armenian border, the Iranian–Armenian border and the Iranian–Azerbaijan border before it finally meet with the Kura River, which flows into the Caspian Sea. This hydrologic region is important for agricultural activities, as the water resource availability and climatic conditions are suitable.

In HR3, Karkheh and Karun are the main rivers. They are the most navigable rivers in Iran, receiving many tributaries. HR3 is an arid and semi-arid region. Jarahi, Zohreh and Sirvan are the other main rivers in the region. Several storage dams have been constructed on the rivers and operated for many years. The region has large water resources but due to poor climatic conditions, agricultural performance is moderate.

In HR4, all the rivers and streams provide relatively moderate water resources for agricultural activities. The Kor River flows into the Bakhtegan Lake at the end of its journey. The rivers Dalaki, Mond and Kol and southern coastal tributaries flow through this hydrologic region and end in the Persian Gulf.

HR5 has no major rivers. The region is classified as very arid. The only important rivers of the region are Halil Rud and Bampoor.

In HR6, the famous Zayandeh Rud is the only main river, which originates from the Zagros Mountains and ends in the Gavkhooni marsh after meandering for 420 km. There is a storage reservoir on the river with an average annual outflow of 47·5 m^3 s^{-1}.

In HR7, Karaj, Jaj Rud, Ghom Rud and Shor Rud are the main tributaries. The rivers originate from both the Alborz and Zagros Mountains and flow toward a salt lake at the central plateau of Iran.

In HR8, Atrak, and Hari Rud are the most important of the six river basins. Atrak is a fast-moving river that begins in the mountains of northeast Iran and flows westwards to end at the southeast corner of the Caspian Sea. Hari Rud is a riparian river recharged from tributaries of both Iran and Afghanistan.

Among all the trans-boundary rivers between Iran and its neighbour countries, only the Hirmand river, located in HR5, was excluded from our modelling study. This is because its contributing area on the Iranian side only accounts for about 14% of the river basin (Chavoshian *et al*., 2005). This will not significantly affect the estimation of internal renewable water resources as the region is quite dry.

Cropping and irrigation Roughly 37 million hectares of Iran's total surface area is arable land, of which 18·5 million hectares are devoted to horticulture and field crop production (Keshavarz *et al*., 2005). About 9 million hectares of this land are irrigated using traditional and modern techniques, and 10 million hectares are rain-fed. Wheat is the core commodity of the Iranian food and agriculture system. It is grown on nearly 60% of the country's arable land. The average yield for irrigated wheat is approximately 3·0 tons ha^{-1}, compared to 0·95 tons ha^{-1} for rain-fed wheat (FAO, 2005).

In Iran, more than 90% of the total water withdrawal is used in the agricultural sector, mostly for irrigation. About 50% of the irrigation water is from surface sources and the other 50% from groundwater (Ardakanian, 2005). Due to the traditional method of irrigation and water conveying systems, the overall irrigation efficiency varies between 15% and 36% (Keshavarz *et al*., 2005). Therefore, a large fraction of diverted water is lost to evaporation and peculation. Irrigation practices in Iran have a large impact on the hydrological balances of the river basins.

In this study, irrigated wheat was incorporated in the modelling in order to obtain a sufficiently accurate representation of the hydrological balances, particularly for areas under irrigated agriculture. According to the information available from the Global Map of Irrigation Areas Version 4·0·1 (Siebert *et al*., 2007) and other sources i.e. USDA (2003) and Statistical Center of Iran (SCI) (1990–2002) the major irrigated areas are distributed across 11 provinces (Table III). Except for Kerman Province (where irrigated wheat is the second largest product in terms of area under irrigated farming), wheat production occupies the largest areas under irrigation in all provinces. In this study, we use winter wheat as a representative crop for irrigated areas. To show the hydrological importance of irrigation, we ran the model with and without taking irrigated wheat into account.

Table III. Proportion of irrigated areas under cultivation of wheat in different provinces (AIW: average (1990–2002) annual area under cultivation of irrigated wheat; TIA: total irrigated area)

Province	(AIW/TIA) × 100
Bushehr	61·27
Esfahan	43·16
Fars	49·10
Ghazvin	47·85
Hormozgan	25·40
Kerman	30·20
Khorasan	53·68
Khozestan	51·28
Sistan Baluchestan	50·82
Tehran	37·35
Yazd	37·47
Zanjan	65·96

Model inputs and model setup

Data required for this study were compiled from different sources. They include: Digital Elevation Model (DEM) extracted from the Global US Geological Survey (USGS, 1993) public domain geographic database HYDRO1k with a spatial resolution of 1 km (http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html); land use map from the USGS Global Land Use Land Cover Characterization (GLCC) database with a spatial resolution of 1 km and distinguishing 24 land use/land cover classes (http://edcsns17.cr.usgs.gov/glcc/glcc.html); and a soil map obtained from the global soil map of the Food and Agriculture Organization of the United Nations (FAO, 1995), which provides data for 5000 soil types comprising two layers (0–30 cm and 30–100 cm depth) at a spatial resolution of 10 km. Further data on land use and soil physical properties required for SWAT were obtained from Schuol *et al*. (2008a). The irrigation map was constructed from the Global Map of Irrigation Areas of the FAO (Siebert *et al*., 2007) which was developed by combining sub-national irrigation statistics with geospatial information on the position and extent of irrigation schemes (http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index10.stm).

Information about the digital stream network and administrative boundaries depicting country and province boundaries and reservoirs/dams was available from the National Cartographic Center of Iran, which provides information at a spatial resolution of 1 km.

Weather input data (daily precipitation, maximum and minimum temperature, daily solar radiation) were obtained from the Public Weather Service of the Iranian Meteorological Organization (WSIMO) for more than 150 synoptic stations. The distribution of the selected stations across the country was sufficiently representative, as the gauging station network was denser in mountainous areas. Periods covered by the available data were from 1977 to 2004. They varied depending on the age of the weather stations. The WXGEN weather generator model (Sharpley and Williams, 1990), which is incorporated in SWAT, was used to fill gaps in the measured records. The weather data for each sub-basin is assigned automatically in SWAT using the closest weather station. River discharge data required for calibration-validation were obtained from MOE of Iran for about 90 hydrometric stations for the period 1977–2002. Historical records on annual yield and area cultivated with irrigated wheat were obtained for the period 1990–2002 from the Agricultural Statistics and the Information Center of Ministry of Jahade-Agriculture (MOJA) and SCI.

A drainage area of 600 km^2 was selected as the threshold for the delineation of watersheds. This threshold was chosen to balance between the resolution of the available information and a practical SWAT project size. This resulted in 506 sub-basins which were characterized by dominant soil, land use and slope. It should be pointed out that with the threshold of 600 km^2, the modelled area does not cover the entire land surface of the country. In particular, the coastal regions and some desert areas have a watershed area of less than 600 km^2. In these cases, the results were linearly extrapolated from the closest modelled sub-basins.

For a better simulation of the hydrology, the daily operation of 19 large reservoirs/dams was incorporated into the model. The operation data and parameters were obtained from the Water Resources Management Organization (WRMO) of Iran.

To simulate crop growth and crop yield, we used the auto-fertilization and auto-irrigation options of SWAT, using the available annual fertilizer-use data from MOJA and assuming that there is no water stress in the production of irrigated wheat. The cumulative heat (growing degree-day) required to reach maturity is almost 2300 for wheat in Iran. The simulation period for calibration was 1990–2002, considering 3 years as the warm-up period. The validation period was 1980–1989, also using 3 years as warm-up period. With the above specifications, a model run took about 15 min of execution time for each run in a 3 Ghz dual-processor PC.

Calibration setup and analysis

Sensitivity analysis, calibration, validation and uncertainty analysis were performed for the hydrology (using river discharge) as well as crop growth (using irrigated wheat yield). As these components of SWAT involve a large number of parameters, a sensitivity analysis was performed to identify the key parameters across different hydrologic regions. For the sensitivity analysis, 22 parameters integrally related to stream flow (Lenhart *et al*., 2002; Holvoet *et al*., 2005; White and Chaubey, 2005; Abbaspour *et al*., 2007) and another 4 parameters related to crop growth (Ruget *et al*., 2002; Ziaei and Sepaskhah, 2003; Wang *et al*., 2005) were initially selected (Table IV). We refer to these as the 'global' parameters. In a second step, these global parameters were further differentiated by soil and land use in order to account for spatial variation in soil and land use (i.e. SCS curve number CN2 of agricultural areas was assigned differently from that of forested areas). This resulted in 268 scaled parameters, for which we performed sensitivity analysis using stepwise regression (Muleta and Nicklow, 2005).

As different calibration procedures produce different parameter sets (Abbaspour *et al*., 1999; Abbaspour *et al*., 2007; Schuol *et al*., 2008b; Yang *et al*., 2008), we used three different approaches for comparison and to provide more confidence in the results. These include: (i) the global approach, where only the global parameters were used (26 parameters); (ii) the scaling approach, where parameters were differentiated by soil and land use (268 parameters); and (iii) the regional approach, where the scaling approach was used in each of the eight hydrologic regions, i.e. each region was calibrated separately.

The SUFI-2 (Abbaspour *et al*., 2007) algorithm was used for parameter optimization according to the above schemes. In this algorithm all uncertainties (parameter, conceptual model, input, etc.) are mapped onto the parameter ranges, which are calibrated to bracket most of the measured data in the 95% prediction uncertainty (Abbaspour *et al*., 2007). The overall uncertainty in the output is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2·5% and 97·5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling. Two indices are used to quantify the goodness of calibration/uncertainty performance: the *P-factor*, which is the percentage of data bracketed by the 95PPU band (maximum value 100%), and the *R-factor*, which is the average width of the band divided by the standard deviation of the corresponding measured variable. Ideally, we would like to bracket most of the measured data (plus their uncertainties) within the 95PPU band ($P\text{-}factor \rightarrow 1$) while having the narrowest band ($R\text{-}factor \rightarrow 0$).

In order to compare the measured and simulated monthly discharges we used a slightly modified version of the efficiency criterion defined by Krause *et al*. (2005):

$$\Phi = \begin{cases} |b|R^2 & \text{for} \quad |b| \le 1 \\ |b|^{-1}R^2 & \text{for} \quad |b| > 1 \end{cases}, \tag{1}$$

where R^2 is the coefficient of determination between the measured and simulated signals and b is the slope of the regression line. For multiple discharge stations, the objective function was simply an average of Φ for all stations within a region of interest:

$$g = \frac{1}{n}\sum_{i=1}^{n}\Phi_i, \tag{2}$$

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Table IV. Initially selected input parameters in the calibration process

Name[a]	Definition	t-value[b]	p-value[c]
v__SURLAG.bsn	Surface runoff lag time (days)	3·091	0·00211
v__SMTMP.bsn	Snowmelt base temperature (°C)	6·448	2.76×10^{-10}
v__SFTMP.bsn	Snowfall temperature (°C)	4·985	8.66×10^{-7}
v__SMFMN.bsn	Minimum melt rate for snow during the year (mm°C^{-1} day^{-1})	2·95	0·00333
v__TIMP.bsn	Snow pack temperature lag factor	2·493	0·013
r__CN2.mgt	SCS runoff curve number for moisture condition II	19·801	2×10^{-16}
v__ALPHA_BF.gw	Base flow alpha factor (days)	2·179	0·02983
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)	2·146	0·03236
v__GW_DELAY.gw	Groundwater delay time (days)	3·633	0·00031
v__GW_REVAP.gw	Groundwater revap. coefficient	2·972	0·00311
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	2·849	0·00457
v__RCHRG_DP.gw	Deep aquifer percolation fraction	5·184	3.20×10^{-7}
v__ESCO.hru	Soil evaporation compensation factor	5·568	4.28×10^{-8}
r__SOL_AWC.sol	Soil available water storage capacity (mm H_2O/mm soil)	8·841	2×10^{-16}
r__SOL_K.sol	Soil conductivity (mm hr^{-1})	2·018	0·04414
r__SOL_BD.sol	Soil bulk density (g cm^{-3})	7·908	1.79×10^{-14}
v__SMFMX.bsn	Maximum melt rate for snow during the year (mm°C^{-1} day^{-1})	0·070	0·944
v__EPCO.hru	Plant uptake compensation factor	1·097	0·273
r__OV_N.hrul	Manning's n value for overland flow	0·004	0·996
r__SOL_ALB.sol	Moist soil albedo	0·241	0·809
v__CH_N2.rte	Manning's n value for main channel	0·871	0·384
v__CH_K2.rte	Effective hydraulic conductivity in the main channel (mm hr^{-1})	0·974	0·330
v__HI	Harvest index	—	—
v__HEAT-UNITS	Crop required heat units	—	—
v__AUTO-WSTRS	Water stress factor	—	—
v__AUTO-NSTRS	Nitrogen stress factor	—	—

[a] v__: parameter value is replaced by given value or absolute change; r__: parameter value is multiplied by (1 + a given value) or relative change (Abbaspour, 2007)
[b] t-value indicates parameter sensitivity: the larger the t-value, the more sensitive the parameter
[c] p-value indicates the significance of the t-value: the smaller the p-value, the less chance of a parameter being accidentally assigned as sensitive

Table V. Calibration performances of regional approach procedure

Hydrologic region	No. stations	Regional approach		
		Goal function	*P-factor*	*R-factor*
HR1	16	0·22	0·40	0·95
HR2	10	0·20	0·52	0·82
HR3	15	0·37	0·62	1·14
HR4	15	0·32	0·65	1·89
HR5	5	0·25	0·64	3·66
HR6	7	0·43	0·43	1·80
HR7	7	0·30	0·46	1·38
HR8	6	0·28	0·47	2·26
Country	81	0·3	0·53	1·52

where n is the number of stations. The function Φ varies between 0 and 1 and is not dominated by a few badly simulated stations. This is contrary to Nash-Sutcliffe, where a large negative objective function (i.e. a badly simulated station) could dominate the optimization process.

The objective function in the global and scaling approaches was optimized based on 81 discharge stations across the modelled area. In the regional approach, the function was optimized using the number of stations that fell within each of the eight hydrologic regions (Table V).

RESULTS AND DISCUSSIONS

Calibration- uncertainty analysis

The sensitivity analysis showed that most of the 22 global parameters of hydrology were sensitive to river discharge. Also, all crop parameters were sensitive to crop yield. These parameters are listed in Table IV along with their t-value and p-value statistics representing their relative sensitivities. As expected, parameters such as CN2 (SCS runoff curve number), temperature parameters and available soil water content (SOL_AWC) were most sensitive. Of the 268 parameters differentiated by soil and land use in the scaling and regional approach, 130 were also sensitive to hydrology and crop yield.

The three calibration procedures produced a similar goodness-of-fit for the whole of Iran in terms of the objective function g, the *P-factor* and the *R-factor*. The optimized parameter ranges, however, were different for the three procedures. Such non-uniqueness is typical for the calibration of hydrologic models. It states that if there is a model that fits the measurements, then there will be many such models with different parameter ranges. Yang *et al.* (2008) used four different calibration procedures, namely GLUE, MCMC, ParaSol and SUFI-2, for a watershed in China. All four gave a very similar goodness-of-fit in terms of R^2, Nash-Sutcliffe, *P-factor* and *R-factor*, but converged to quite different parameter ranges. In this study, where only SUFI-2 was used with

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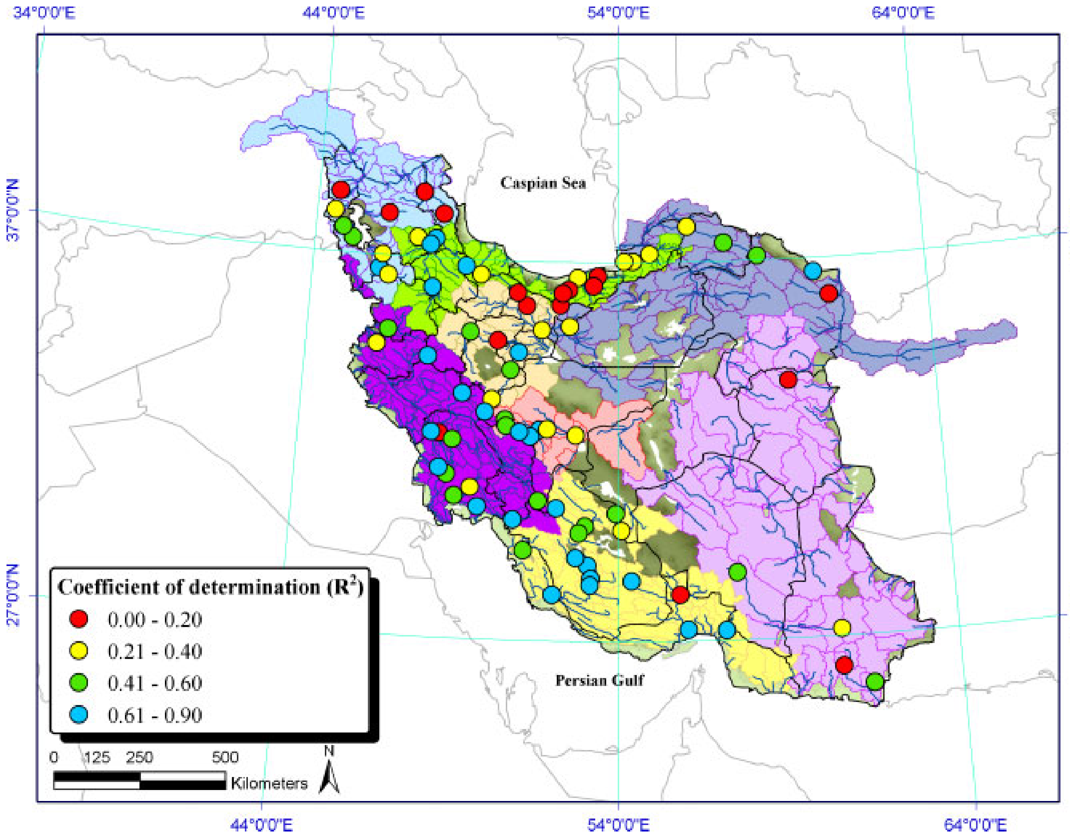

Figure 2. Comparison of observed and simulated discharges using coefficient of determination (R^2) for 81 stations across the country, resulting from the regional approach calibration procedure

three different objective functions, all three procedures resulted in different final parameter values similar to the study of Schuol *et al.* (2008b) for Africa.

In the following, we used the result of the regional approach because the eight regions accounted for more of the spatial variability in the country and a slightly better objective function compared to other approaches.

Table V presents the calibration results for the regional approach. On average, 53% of the data from 81 discharge stations fell within the 95PPU. The *R-factor* was 1·52. Figure 2 shows the coefficient of determination (R^2) for the individual discharge stations across the country. Most of the stations in HR3, HR4, and HR6 were described with an R^2 of more than 0·5. There are still some poorly simulated stations with R^2 values of less than 0·15. The small *P-factor* and large *R-factor* values for these stations represent large uncertainties. Based on the information we obtained by consulting the local experts, possible reasons for the poor model calibration in some regions include insufficient accounting of agricultural and industrial water use in the model, inter-basin water transfer projects in humid and arid zones (Abrishamchi and Tajrishi, 2005), and the construction or operation of more than 200 reservoirs in the country during the period of study (Ehsani, 2005).

We constructed a water management map for the country for the period of study as illustrated in Figure 3. This management map shows the spatial distribution of some of man's activities influencing natural hydrology during the period of study. Regions with the highest activities have the worst calibration/validation results (compare with Figure 2) as well as the largest uncertainties. The construction of dams, reservoirs, roads and tunnels can affect the local hydrology for many years. This is an important and often neglected source of uncertainty in large-scale hydrological modelling. As the extent of management in water resources development increases, hydrological modelling will become more and more difficult and will depend on the availability of detailed knowledge of the management operations.

Calibration of a large-scale distributed hydrologic model against river discharge alone may not provide sufficient confidence for all components of the water balance. Multi-criteria calibration is suggested by Abbaspour *et al.* (2007) for a better characterization of different components and as a way of dealing with the non-uniqueness problem (narrowing of the prediction uncertainty). Because of the direct relationship between crop yield and evapotranspiration (Jensen, 1968; FAO, 1986), we included yield as an additional target variable in the calibration process in order to improve the simulation of ET, soil moisture and deep aquifer recharge.

Figure 4 shows the calibration results for the winter-wheat yield across 12 major irrigated-wheat producing provinces. As illustrated, observed yields for all provinces are inside or very close to the predicted bands indicating good results. We are assuming that if yield is correct, then

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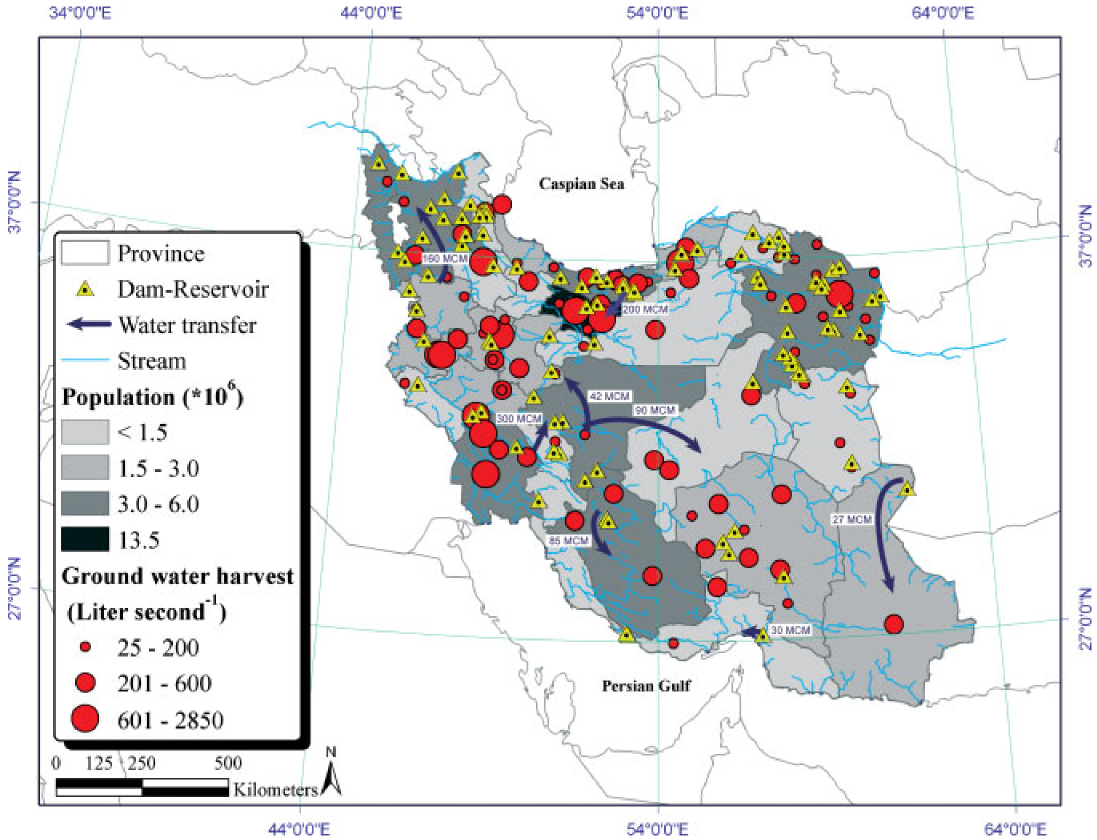

Figure 3. Water management map of the country showing some of man's activities during the period of study. The map shows locations of dams, reservoirs, water transfers and groundwater harvest (background shows Provincial-based population)

actual evapotranspiration and also soil moisture are simulated correctly. This in turn indicates that deep aquifer recharge is correct, hence increasing our confidence on the calculated blue water i.e. the sum of river discharge and deep aquifer recharge.

For validation (1980–1989), we used the parameters obtained by the regional approach to predict river discharges at the stations not affected by upstream reservoirs. Only these stations were chosen because data on daily outflow from reservoirs were not available for the validation period. In Figure 5, some examples of calibration and validation results are illustrated for individual stations in HR1-3. In general, the results of calibration and validation analysis based on river discharge and crop yield were quite satisfactory for the whole country. Next, we calculated water resources using the calibrated model and compared it with the available data as a further check of the performance of the model.

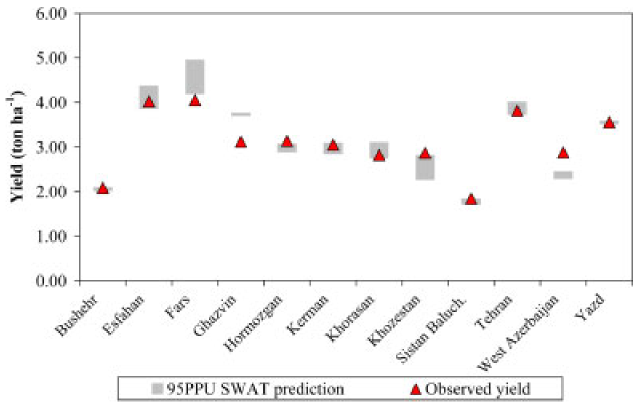

Figure 4. Comparison of observed and simulated (expressed as 95% prediction uncertainty band) annual wheat yield averaged over the years 1990–2002 for different provinces

Quantification of water resources at provincial and regional level

Monthly internal renewable blue water resources (IRWR, the summation of water yield and deep aquifer recharge) were calculated for all 506 sub-basins included in the model. Furthermore, the monthly IRWR of sub-basins were aggregated to estimate the regional, provincial and national IRWR availability. Figure 6 compares the predicted regional IRWR with the values published by MOE (1998) and the prediction for the whole country with MOE and FAO estimates (FAO, 2003; Banaei *et al*., 2005). The MOE estimate is based on the long term (1966–1994) averages of net precipitation, which is annual precipitation minus annual evapotranspiration. The FAO estimates are based on long-term (1961–1990) averages of annual surface and groundwater flow generated from precipitation. As shown in Figure 6, the FAO and MOE estimates are within or close to the 95PPU of our model predictions. Confidence in model results increases as most of the observed wheat yield (Figure 4) and IRWR fall within the uncertainty band of model prediction.

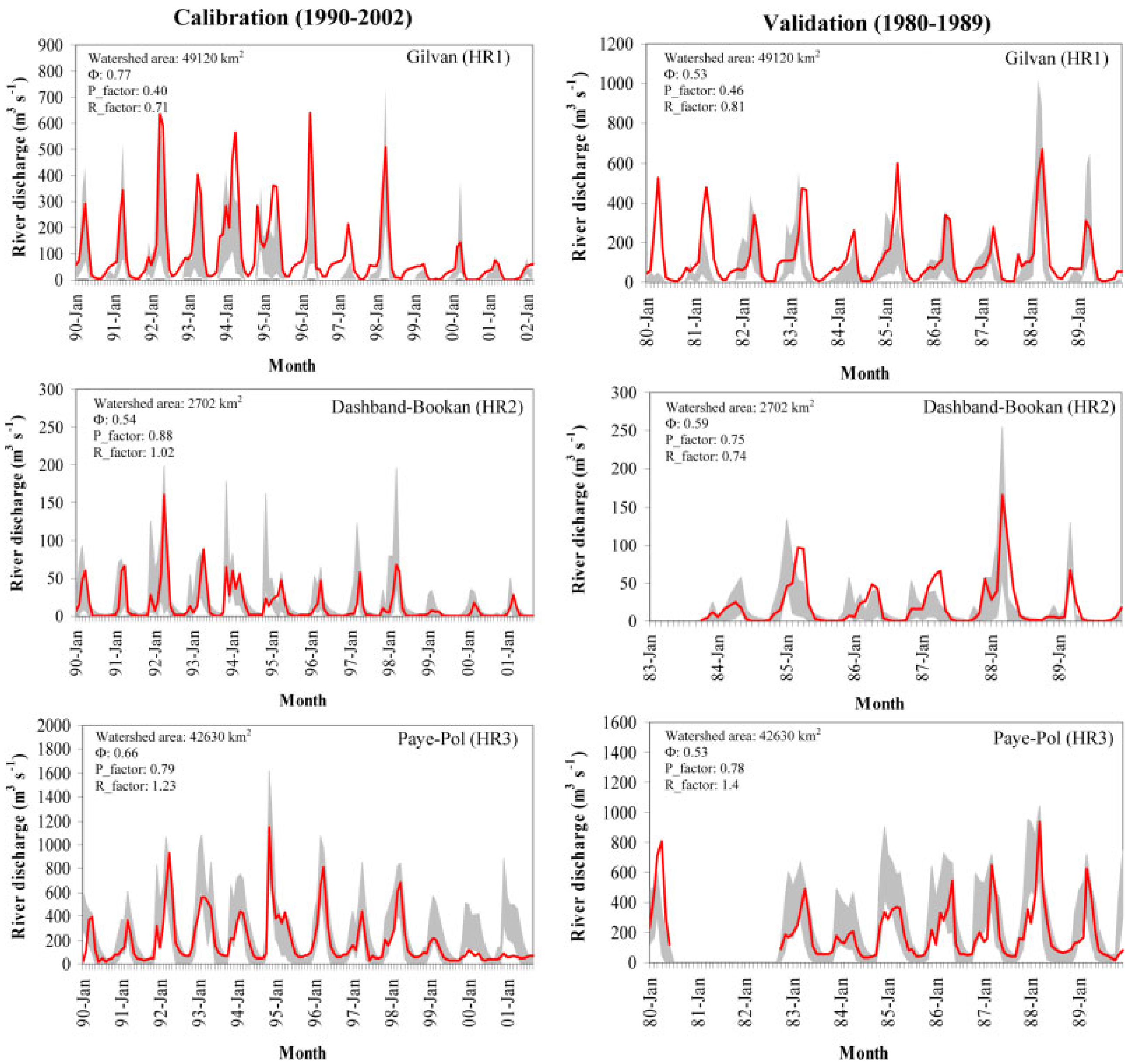

Figure 5. Comparison of the observed (red line) and simulated (expressed as 95% prediction uncertainty band) discharges for three hydrometric stations located in hydrologic regions HR1, HR2 and HR3. Calibration (left) and validation (right) results are shown

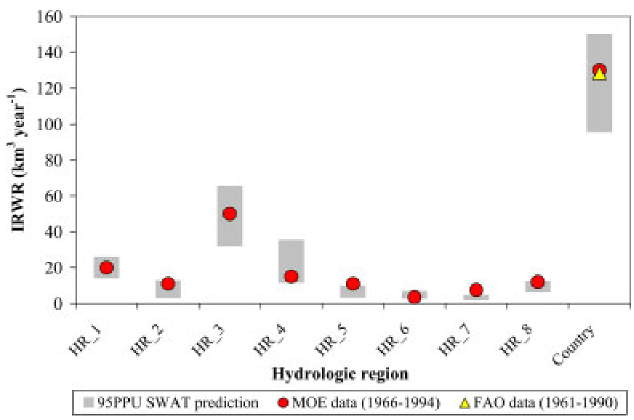

Figure 6. Comparison of simulated average (1990–2002) annual regional internal renewable blue water resources (IRWR) with the available data from the Ministry of Energy (MOE) and FAO for the entire country

Figure 7 shows the IRWR and actual ET or green water flow (Falkenmark and Rockstrom, 2006) for 30 provinces. For a better inter-provincial comparison we show also annual precipitation. In general, for some provinces uncertainty ranges of average annual IRWR are wide and this is especially true for the provinces with higher precipitation. Similar results were also shown by Schuol *et al*. (2008a, b) in their study of water resources in Africa.

A larger uncertainty band for some provinces might be due to higher conceptual model uncertainty as water management projects (not included in the model) could alter natural hydrology as discussed previously. A comparison of the results in Figure 7 and the 'water management map' in Figure 3 shows the correspondence between high uncertainty provinces and the ones with substantial managements. It should be noted that the reported

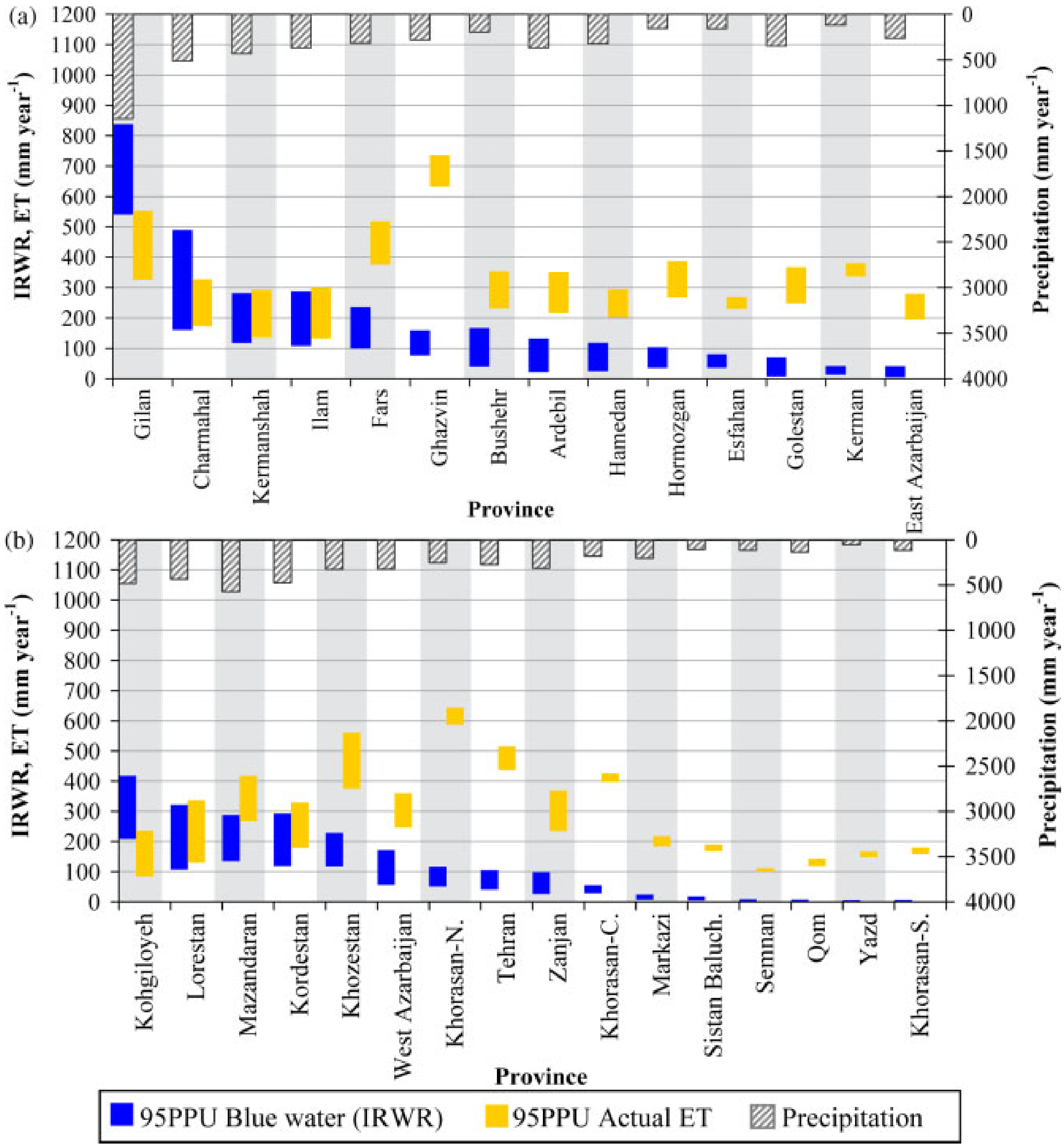

Figure 7. Modelled average (1990–2002) annual provincial internal renewable blue water resources (IRWR), actual evapotranspiration (ET) expressed as 95% prediction uncertainty and precipitation

uncertainty includes both modelling uncertainties as well as natural heterogeneity. Despite the uncertainties, our results are quite realistic for most provinces as they were evaluated and confirmed by local experts (Communications with local water resources experts, 2007).

We found that irrigation in particular has a large impact on hydrologic water balance. The main advantage of accounting for irrigated agricultural areas in the model is that actual ET and soil water are simulated adequately. For example, in the Zayandeh Rud river basin (Esfahan Province, HR6) the annual precipitation has an average of 126 mm. This river basin is agricultural and is intensively irrigated from various surface and groundwater sources. By ignoring irrigation, therefore, we could never produce an ET value of over 1000 mm per year as reported by Akbari *et al*. (2007). This would have created an incorrect picture of water balance in this region. To illustrate the impact of irrigation on water balances, we performed simulations with and without irrigation in the model.

An example is shown in Figure 8 for the Esfahan province. Using the 95PPU band, the difference between ET with and without irrigation was calculated to have an average value of about 130 mm per year for the entire province. The difference becomes much larger if we take individual basins under irrigated agriculture within the province. For example, for the Zayandeh Rud river basin the calculations of ET with and without irrigation gave average values of about 850 mm and 135 mm per year, respectively. Aside from the bulk figures, the temporal distribution of the two scenarios shows pronounced differences, as illustrated in Figure 8.

Quantification of water resources at sub-basin level

For a general overview of the hydrological components in the country at sub-basin level we constructed Figure 9. The average of the 95PPU interval for the

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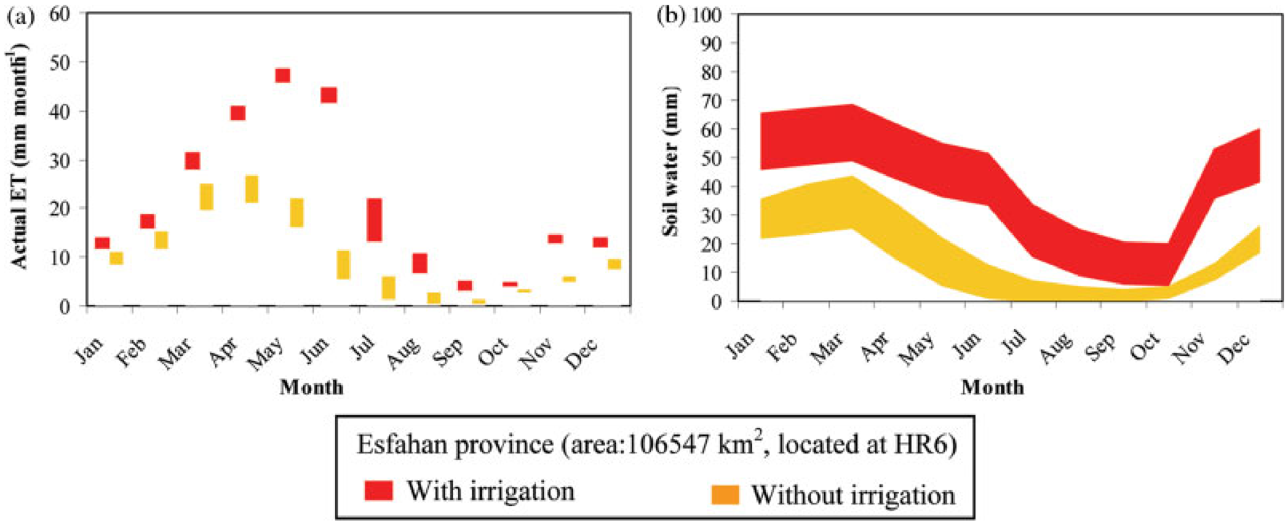

Figure 8. Illustration of the differences in (a) predicted actual ET and (b) soil moisture with and without considering irrigation in Esfahan province (monthly averages for the period of 1990–2002)

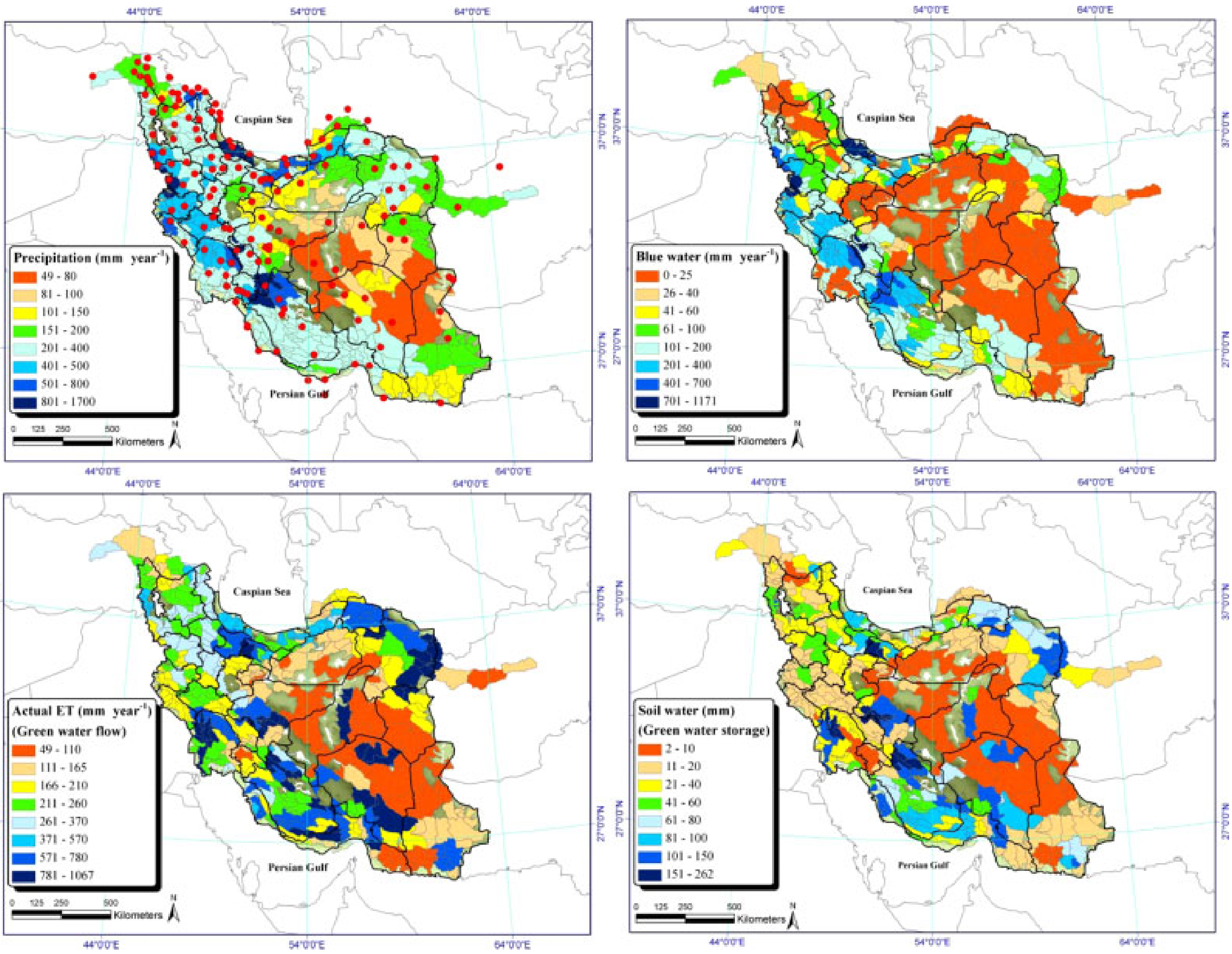

Figure 9. Average (1990–2002) simulated annual precipitation, internal renewable blue water resources (IRWR), actual evapotranspiration (ET) and soil water at sub-basin level for the entire country

years 1990–2002 was used to characterize the spatial distribution of various components such as precipitation, blue water, actual evapotranspiration and soil water. In the precipitation map, spatial distribution of the rain gauge stations is also shown. The average precipitation for each sub-basin was calculated from the closest station. There is a pronounced variation in the spatial distribution of the hydrological variables

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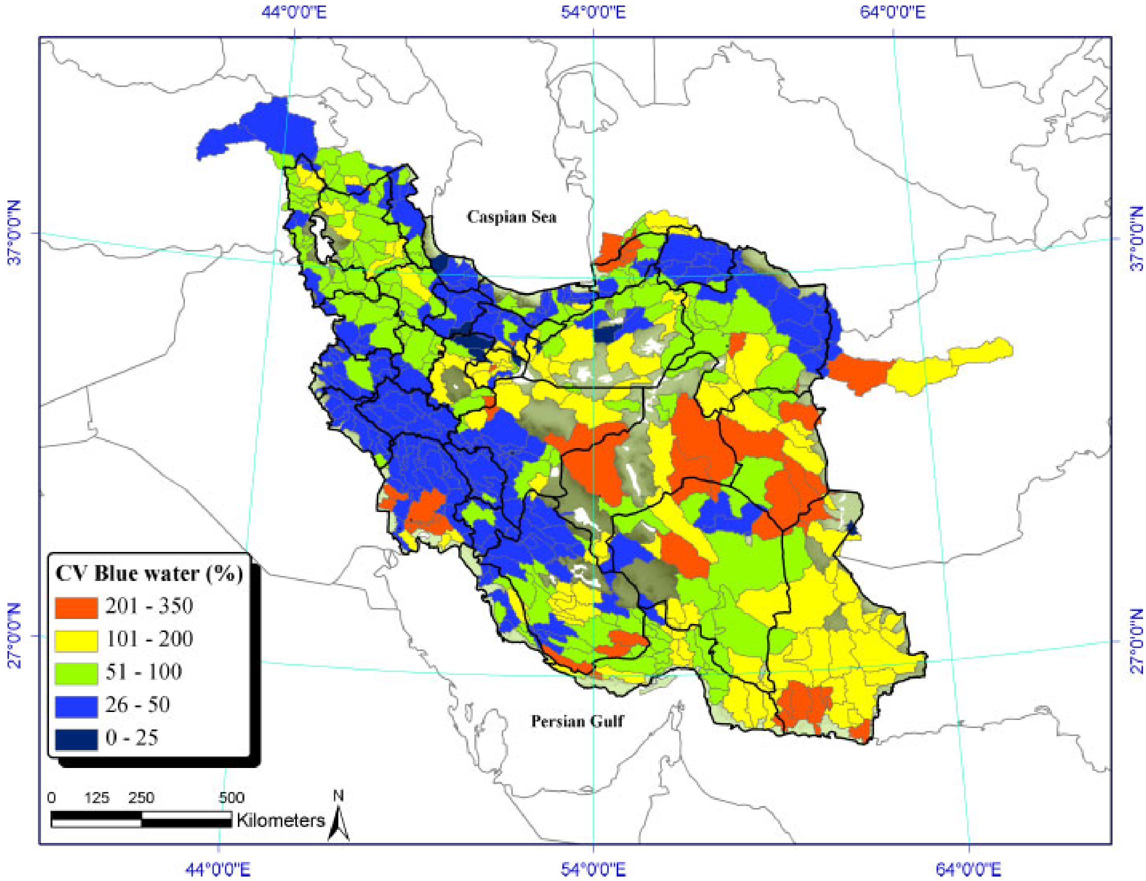

Figure 10. Coefficient of variation (CV) of the modelled annual (1990–2002) internal renewable blue water

across the country. In many sub-basins in the north-east and central Iran, where precipitation and blue water resources are small, actual evapotranspiration is large mainly due to irrigation from other water sources such as reservoirs and groundwater. The soil water map in Figure 9 shows areas where rain-fed agriculture has a better chance of success due to larger soil moisture.

To further illustrate the annual variations of blue water availability from 1990 to 2002, the coefficient of variation (CV in %) was calculated as follows and presented in Figure 10:

$$CV = \frac{\sigma}{\mu} \times 100, \tag{3}$$

where σ is the standard deviation and μ is the mean of annual IRWR values for each sub-basin. CV is an indicator of the reliability of the blue water resources from year to year. A large CV indicates a region experiencing extreme weather conditions such as drought, hence having an unreliable blue water resource for development of rain-fed agriculture. Figure 10 shows that central, eastern and southern parts of Iran fall into this category and have a high risk of food production in the absence of irrigation.

To highlight the country's water scarcity situation, we plotted in Figure 11 the per capita internal renewable blue water availability in every sub-basin. For this we used a 2·5 arcmin population map available from the Center for International Earth Science Information Network in 2005 (CIESIN, http://sedac.ciesin.columbia.edu/gpw). As calculated here for the entire country, the 95% prediction uncertainty of (blue) water resources availability (calculated from 1990–2002) stood at 1310–2060 m^3 per capita based on the population estimate in 2005.

The spatial distribution of water resources availability in Figure 11, however, shows a large variation across the country. The five water stress levels given in the figure follow the widely-used water stress indicators defined by Rijsberman (2006), Falkenmark *et al.* (1989) and Revenga *et al.* (2000). Taking 1700 m^3 per capita per year as the water scarcity threshold, about 46 million people living on about 59% of the country's area are subject to water scarcity. According to the Global Geographic Distribution Map of Major Crops (Leff *et al.*, 2004), which has a spatial resolution of 5 arcmin and the findings from this study, about 53% of the area under cultivation of wheat in Iran is located in water-scarce sub-basins. Of the total wheat production in the country, 4·4 million tones of irrigated wheat and 1·9 million tons of rain-fed wheat are produced every year in water-scarce regions. In such a vulnerable situation of water resources availability, it can be expected that self-sufficiency in terms of wheat production will become even more difficult in the future, and the looming impact of climate change will further worsen the situation. All the more, it is of great

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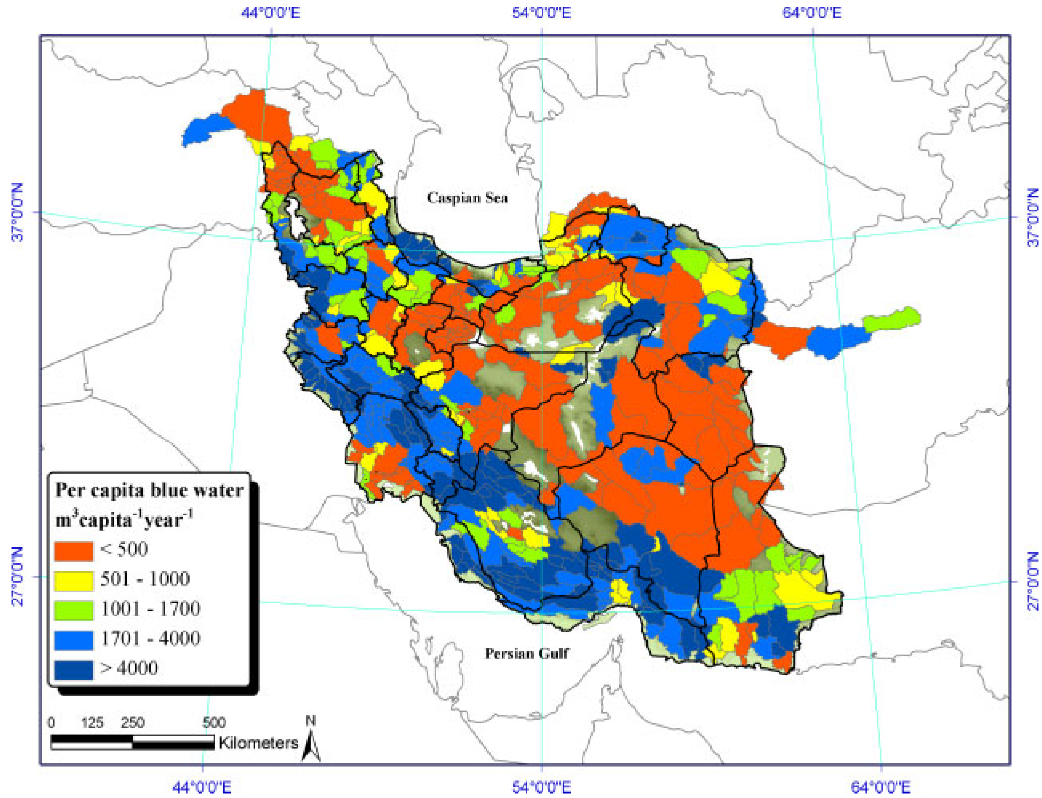

Figure 11. Per capita blue water availability at 506 modelled sub-basins. Values of <500 indicate severe water stress, <1000 are high water stress, 1700 is water stress threshold and >1700 indicates adequate water availability

importance to balance water budgets in water-scarce regions and to improve the efficiency of water resources utilization.

SUMMARY AND CONCLUSION

Water resources availability, including internal renewable blue water, actual and potential ET as well as soil water, was estimated for Iran at the sub-basin spatial and monthly temporal resolutions. The water components were then aggregated at sub-provincial, provincial, regional and country levels.

The study was performed using the process-based semi-distributed hydrologic model SWAT, which integrates hydrological, agricultural and crop growth processes. Extensive calibration and validation as well as sensitivity and uncertainty analyses were performed to increase the reliability of the model outputs. The model was calibrated against crop yield as well as river discharge taking account of dam operation. Inclusion of irrigation was found to be essential for an accurate accounting of actual ET and soil water. SUFI-2 was used to calculate 95% prediction uncertainty band for the outputs to characterize model uncertainty. Considering the conceptual model uncertainty (e.g. inter-basin water transfer, water use) as well as input data uncertainty and parameter uncertainty in such a large-scale hydrological model, presentation of the freshwater availability as 95PPU band is useful for the water resources management and planning in the individual regions and for the country as a whole.

This study provides a strong basis for further studies concerning water and food security in Iran. Producing more food with increasing water scarcity is a daunting challenge to the country. Water resources availability and wheat yield across provinces/regions in Iran as well as water scarcity distribution were successfully estimated, laying the basis for a systematic assessment of crop water productivity. Among other measures, scenario analysis could be used with the current study to support the evaluation of the potential improvement in the regional and national water productivity and water-use efficiency through regional crop structure adjustment and regional virtual water trade. The modelling approach in this study could be used for a high-resolution analysis of water resources and a unified analysis of the blue and green water in other arid and semi-arid countries.

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