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**ASSESSMENT OF REGIONAL WATER ENDOWMENTS,
CROP WATER PRODUCTIVITY, AND IMPLICATIONS
FOR INTRA-COUNTRY VIRTUAL WATER
TRADE IN IRAN**



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**ASSESSMENT OF REGIONAL WATER ENDOWMENTS, CROP
WATER PRODUCTIVITY, AND IMPLICATIONS FOR INTRA-
COUNTRY VIRTUAL WATER TRADE IN IRAN**

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SUMMARY

Population growth and economic development are increasing demand for water resources. Although there is no global water scarcity as such, an increasing number of regions in arid and semi-arid countries are chronically short of water. Given this state of scarcity, agriculture as the biggest water user is becoming under severe scrutiny to account for the water it uses. As the demand for food is ever increasing, and there is no significant room to expand areas of cultivation, the increasing demand for food will have to be met through improved management of the available and limited resources, and/or through imports from outside.

Characterized by an arid and semi-arid environment, Iran is one of the countries stressed by an increasing water scarcity. Limitations in water resources are posing a major constraint to the expansion of crop land and food production in Iran. Agriculture is by far the largest water user in Iran, accounting for more than 90% of the total water withdrawal. Increasing the production of cereal crops, however, is of vital national interest. Wheat is the main food crop, and self-sufficiency in wheat production is a national objective of prime importance. Although this goal was temporarily achieved in 2004, there is general doubt about Iran's ability to sustain this level of production in view of the increasing water scarcity and other obstacles. In general, agricultural water use efficiency is low in Iran (i.e. 15%-36%). Efforts to increase agricultural water use efficiency have been made through increasing crop water productivity (*CWP*) at plant and field levels, but this has not so far alleviated the water scarcity in the country.

This thesis addresses the issue of water scarcity by looking for ways of alleviating it through virtual water trade strategy (VWTS) across regions/provinces within the country. This strategy calls in part for the adjustment of the structure of cropping pattern (ASCP) and interregional food trade where crop yield and crop water productivity as well as local economic and social conditions are considered. The core of VWT is the idea that intensive crops are produced in the regions with high *CWP* and exported to the regions with low *CWP*. Hence, water scarce regions import water-intensive products rather than producing them locally for optimum utilization of their limited water resources. VWTS can be considered as an instrument to overcome the imbalances of water availability across regions. We consider the intra-country VWTS as a policy option to mitigate the chronic water shortages in water scarce regions of Iran. This calls for an adjustment in the structure of cropping production within the country. A sound knowledge of water

resources availability and crop water use is a necessary basis for adjusting cropping structures across regions in line with the VWTS. New modeling tools allow the assessment of large scale, complex, and intensively managed systems.

The main goal of this study was to examine the feasibility of applying intra-country VWTS to alleviate water shortage in Iran. To attain this goal, the specific objectives were: i) to model the temporal and spatial availability of different water resources components such as blue water flow, green water flow and green water storage; ii) to assess the impact of the climate change on water availability; iii) to model cereal crop yields and crop water productivity in Iran at a high spatial and temporal resolution; and iv) to construct a systematic framework for regional crop structural adjustment that is in line with the VWTS.

In the first part of this study the Soil and Water Assessment Tool (SWAT) was used 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 conducted to assess the performance of the model. The results were satisfactory for most of the river basins 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 the sub-basin level with monthly time steps. The spatially aggregated water resources and simulated wheat 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 and must be considered in the SWAT model. 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.

To obtain the second objective, climate scenarios were generated for the periods 2010-2040 and 2070-2100 using the Canadian Global Coupled Model (CGCM 3.1). We chose scenarios A1B, B1 and A2 for the climate projection. They were downscaled for 37 climate stations across the country. The calibrated hydrologic model was then applied to the specified periods to analyze the effect of future climate on precipitation, blue water, green water, and wheat yield across the country. We found that wet regions of the country will, in general, receive more rainfall while dry regions will receive less. Analysis of daily rainfall intensities indicated more frequent larger-intensity floods in the

wet regions and more prolonged droughts in the dry regions. When aggregated to provincial levels, the differences in predictions due to the three future scenarios were smaller than the uncertainty in the hydrologic model. However, at the sub-basin level the three climate scenarios produced quite different results for dry regions of the country, while the results were more or less similar for wet regions.

To achieve the third objective we modeled the yield for irrigated and rainfed wheat (Y) and consumptive water use (ET) at a sub-basin 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 various policies to improve the agricultural system in Iran. Our analysis of the ratio of water use to internal renewable water resources revealed that 23 out of 30 provinces are using more than 40% of their water resources for agriculture. Twelve provinces reach a ratio of 100% and more, indicating severe water scarcity and groundwater resource depletion. An analysis of Y - CWP relationship showed that a better water management in rainfed wheat, where yield is currently small, could lead to a larger marginal return for 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 the AWC through proper soil management practices. This will save about 5-6% of the total irrigation water use for wheat, when aggregating to national level. Furthermore, we estimated the water required to reach wheat self-sufficiency by the year 2020 (keeping all factors except population constant). The results showed that 88% of the additional wheat production would need to be produced in water-scarce provinces. Therefore, a strategic planning in the national agricultural crop production and food trade to ensure sustainable water use is needed.

In the last part of this study, we constructed a systematic framework to assess the adjustment to the structure of cropping pattern (ASCP) that are in line with the VWTS under various driving forces and constraints. A “mixed-integer, multi-objective, linear optimization model” was developed and solved by linear programming (LP), using Lingo 9 software. The annual data for 1990-2004 were used to account for yearly fluctuations of water availability and food production. Five scenarios were designed for adjusting provincial cropping structure to maximize national cereal production while meeting certain levels of wheat self-sufficiency under various water and land constraints. In these scenarios we accounted for the performance of individual provinces in crop yield and crop water productivity. The results showed that Iran could follow a sustainable water use policy while producing an amount of cereal equivalent to the average production in

the study period covering about 90% of what is needed for wheat self-sufficiency. This is larger than the average (76%) during the study period. However, the scenario that assumes a substantial improvement in irrigation water use efficiency suggests a promising outcome in terms of sustaining the country's total cereal production and achieving 100% wheat self-sufficiency while alleviating water stress in water scarce provinces. Based on the adjusted cropping structures in the various scenarios studied, we quantified the amount of virtual water that could be transferred from surplus provinces to deficit provinces. At the national level, depending on the scenarios, wheat surplus provinces as a whole could compensate 31% to 100% of the total wheat shortage in the deficit provinces. As a result, wheat-deficit provinces would receive $3.5 \times 10^9 \text{ m}^3$ to $5.5 \times 10^9 \text{ m}^3$ of virtual water by importing wheat from the surplus provinces.

ZUSAMMENFASSUNG

Bevölkerungswachstum und wirtschaftliche Entwicklung führen in den meisten Entwicklungsländern zu einem steigenden Bedarf an Wasserressourcen, die vor allem in semiariden und ariden Gebieten ohnehin bereits sehr knapp sind. Zusätzliche landwirtschaftliche Nutzflächen sind gewöhnlich kaum vorhanden, so dass der steigende Nahrungsmittelbedarf primär mit Hilfe verbesserten Managements der knappen verfügbaren Wasserressourcen gedeckt werden muss. Als mehrheitlich arides bis semi-arides Land hat auch Iran nur sehr begrenzte Wasserressourcen, was die wesentlichste Einschränkung für eine Ausweitung der Kulturlächen und damit auch der Nahrungsmittelproduktion darstellt. Die Landwirtschaft beansprucht mit 90% des gesamten Wasserverbrauchs den grössten Anteil dieser Ressource. Obwohl Selbstversorgung in der Produktion von Weizen ein erklärtes Ziel der iranischen Politik ist und eine solche im Jahr 2004 auch tatsächlich einmal erreicht wurde, bestehen angesichts der zunehmenden Wasserknappheit und anderer Einschränkungen grundlegende Zweifel, dass dieses Ziel auch in Zukunft aufrechtzuerhalten ist. Grundsätzlich ist die Effizienz in der Wassernutzung der Landwirtschaft gering (i.d.R. 15-36%). Alle Anstrengungen zur Steigerung der Effizienz, namentlich in der Pflanzen-Wasser-Produktivität (engl. crop water productivity, CWP) konnten die angespannte Wassersituation im Land bisher nicht lindern.

Die hier vorliegende Studie befasst sich mit dem Thema Wasserknappheit und ihrer Auswirkungen auf die Nahrungsmittelproduktion unter dem Gesichtspunkt des virtuellen Wasserhandels (engl. virtual water trade, VWT) als mögliche Strategie eines möglichst effizienten Umgangs mit der Ressource Wasser. Die Strategie des VWT beruht darauf, dass Pflanzen in Regionen mit hohem CWP angebaut und in Regionen mit tiefem CWP exportiert werden. Dies führt dazu, dass wasserarme Regionen wasserintensive Pflanzenprodukte importieren anstatt sie lokal zu produzieren, was eine optimale Nutzung der begrenzten lokalen Wasserressourcen erlaubt. Landesweit gesehen ist so ein Ausgleich in der ungleich verteilten Ressource Wasser zwischen den verschiedenen Regionen möglich. Die Neuzuteilung der Produktionsstandorte und -mengen erfordert aber eine genaue Kenntnis der lokal vorhandenen Ressourcen und Infrastrukturen. Dies ist mit den heute zur Verfügung stehenden Modellierungstechniken auch auf grosser Skala für intensiv bewirtschaftete und komplexe Agrarsysteme möglich.

Das Hauptziel dieser Arbeit war es zu untersuchen, ob VWT innerhalb eines

Landes eine durchführbare Option zur Linderung der Wasserknappheit ist. Im Rahmen dieser allgemeinen Zielsetzung wurden als Teilziele die Verfügbarkeit an Wasserressourcen, der Einfluss des Klimawandels auf die künftige Wasserverfügbarkeit, und die räumliche Verteilung der Getreideproduktion und ihre Beziehung zur Wasserverfügbarkeit im Iran untersucht, sowie ein systematischer Rahmen für eine VWT-Strategie innerhalb des Landes erstellt.

Hierzu wurde mit Hilfe des Soil Water Assessment Tools (SWAT) ein hydrologisches Modell des Studiengbietes (Iran) erstellt und mittels Abflussmessungen und Getreideertrag kalibriert, wobei auch Staudämme und Bewässerungen berücksichtigt wurden. Eine Unsicherheitsanalyse zeigte, dass die Qualität der Modellresultate für die meisten Flüsse im Land zufriedenstellend war. Das erstellte Modell quantifiziert in monatlichen Zeitschritten auf der Ebene von Einzugsgebieten die Flüsse an „blauem Wasser“ (insbesondere Eintrag an Wasser und Grundwasserneubildung), die Flüsse an „grünem Wasser“ (insbesondere Evapotranspiration) und die Speicherung von grünem Wasser (Bodenwasser). Die auf Ebene Provinzen aggregierten Resultate bezüglich Wasserressourcen und Getreideerträgen stimmten gut mit vorhandenen statistischen Daten überein. Für die Kalibration wurde die Periode 1990-2002 und für die Validation die Periode 1980-1989 gewählt. Die Modellrechnungen ergaben, dass in Gebieten mit künstlicher Bewässerung die Bewässerungsmethode einen wesentlichen Einfluss auf die lokale Wasserbilanz hat und dass dies im SWAT-Modell berücksichtigt werden muss und dass 55% des bewässerten Weizens und 57% des unbewässerten Weizens des Grundnahrungsbedarfes in Regionen mit akuter Wasserknappheit angebaut werden.

Um das zweite Teilziel dieser Arbeit zu erreichen, wurden Klimaprognosen des Canadian Global Coupled Model (CGCM 3.1) für die Zeiträume 2010-2040 und 2070-2100 auf 37 Klimastationen in Iran heruntergerechnet. Dazu wurden die Klimaszenarien A1B, B1 und A2 des CGCM 3.1 verwendet. Für jedes der Szenarien wurde dann mit dem SWAT-Modell der zu erwartende Effekt des prognostizierten Klimawandels auf den Niederschlag, die Flüsse an blauem und grünem Wasser sowie auf die Getreideerträge bestimmt. Grundsätzlich kann auf Grund dieser Rechnungen für alle Szenarien gesagt werden, dass es in den feuchteren Regionen in Zukunft mehr und in trockeneren Gebieten noch weniger Niederschlag zu erwarten ist. Zudem ist zu erwarten, dass es in den feuchteren Gebieten zu häufigeren und grösseren Fluten kommen wird, während dem die Dürren in den trockeneren Gebieten länger anhalten werden. Auf regionaler Ebene ergaben sich Unsicherheiten in den Vorhersagen, die grösser waren als die Unterschiede

zwischen den einzelnen Klimaszenarien. Nur für die trockeneren Gebieten ergaben die verschiedenen Szenarien grössere Differenzen, während sie sich für die feuchteren Gebiete in ihren hydrologischen Auswirkungen kaum unterschieden.

Im dritten Teil der Arbeit wurden die Erträge an Weizen und der Wasserverbrauch in künstlich bewässerten und allein durch Regenwasser versorgten Kulturen untersucht. Daraus wurde dann die Wasserproduktivität für den Weizenanbau auf der Ebene der Einzugsgebiete berechnet. Es ergab sich, dass in 23 von 30 Regionen in Iran mehr als 40% der erneuerbaren Wasserressourcen für die Bewässerung verwendet werden. In 12 Regionen überstieg dieses Verhältnis sogar 100%, was nicht nur eine gravierende Wasserknappheit, sondern darüber hinaus auch eine Übernutzung der Grundwasserreserven anzeigt. Die Betrachtung des Verhältnisses zwischen Getreideertrag und CWP zeigt, dass sich in 18 der 30 Regionen durch besseres Wassermanagement der regenbewässerten Anbauflächen, auf welchen der Ertrag zur Zeit gering ist, der Ertrag an Weizen bei gleich bleibendem Wasserverbrauch noch stark steigern liesse und sich durch eine Verbesserung der Bodenbewirtschaftung zudem die Wasserspeicherfähigkeit des Bodens erhöhen liesse. Um abzuschätzen, ob die angestrebte Selbstversorgung mit Getreide bis ins Jahr 2020 realistisch ist, wurde der dazu notwendige Wasserbedarf bestimmt, wobei das Wachstum der Bevölkerung berücksichtigt, aber sonstige Faktoren konstant gehalten wurden. Dabei zeigt sich, dass 88% der erforderlichen Mehrerträge in wasserarmen Regionen produziert werden müssten. Dies dürfte nur mit einer entsprechenden strategischen Planung der nationalen landwirtschaftlichen Produktion möglich sein, in der eine nachhaltige Wassernutzung sichergestellt ist.

Der letzte Teil dieser Arbeit befasst sich damit, wie die räumliche Verteilung der Anbauggebiete für Getreide angepasst werden müsste, um mittels VWT unter verschiedenen Randbedingungen und Einschränkungen eine möglichst hohe Getreideproduktion bei möglichst geringem Wasserverbrauch zu erreichen. Um dieses „multi-objective optimization problem“ in der Anpassung in der räumlichen Struktur der landwirtschaftlichen Pflanzenproduktion (engl. crop structure adjustment, CSA) auf nationaler Ebene zu erreichen, wurde die Methode der linearen Programmierung (LP) mit Hilfe der Software Lingo 9 verwendet. Um von jährlichen Schwankungen in der Wasserverfügbarkeit und der Lebensmittelproduktion möglichst unabhängig zu sein, wurde die Periode 1990-2004 als Bezugsperiode verwendet. Die CSA-Optimierung wurde für 5 verschiedene Szenarien durchgeführt. Ziel war es jeweils, die nationale

Getreideproduktion zu maximieren, wobei jedoch in den einzelnen Regionen unter je nach Szenario verschiedenen Bedingungen ein Minimum an Selbstversorgung mit Weizen einzuhalten war. Tendenziell führten die Optimierungsrechnungen wie erwartet dazu, dass die Anbaufläche eines Getreides in Regionen, in welchen der Ertrag und der CWP über dem nationalen Durchschnitt lag, erhöht und in Regionen mit unterdurchschnittlichem Ertrag und CWP zu verringert werden müsste. Die Analysen ergaben, dass der Iran im Jahr 2020 eine Selbstversorgungsquote von 90-92% erreichen könnte, gegenüber 87% Selbstversorgung im Referenzzeitraum, ohne die Wasserknappheit zu verschärfen. Bei substanzieller Verbesserung der Bewässerungseffizienz könnte sogar 100% Selbstversorgung erreicht und gleichzeitig die Knappheit an Wasser verringert werden.

Je nach Szenario würden Regionen mit Weizenüberschuss 31-100% des Weizenmangels in den Regionen mit ungenügender Produktion ausgleichen. Dabei würden Regionen mit einem Defizit zwischen $3.5 \times 10^9 \text{ m}^3$ und $5.5 \times 10^9 \text{ m}^3$ virtuelles Wasser durch Importe aus den Regionen mit Weizenüberschuss erhalten.

1 Introduction

1.1 Background and motivation

Population growth and industrialization on the one hand and extended drought, environmental concerns, and a possible adverse impact of climate change on the other hand are the major limiting factors of the water resources to secure food production in developing countries of arid and semi-arid regions (Rosegrant et al., 2002; IPCC, 2001). With no significant room to expand areas of cultivation in these regions, increased demand for food will have to be met through improved management of the available and limited resources (Qadir, et al., 2007) and/or from import from outside (Yang and Zehnder, 2007; Allan, 1996).

Characterized by an arid and semi-arid environment, Iran is enduring increasing water scarcity, which has posed a major constraint to the expansion of crop land and food production. Agriculture is by far the largest water user in Iran, accounting for more than 90% of the total water withdrawal. Despite the scarce water resources availability, wheat self-sufficiency has been a desired national objective and the goal was temporarily achieved in 2004. However, there is a general doubt about Iran's ability to maintain this level of production amid the mounting water challenges, among other obstacles. In general, the agricultural water use efficiency is low in Iran. The average irrigation and conveyance efficiency is around 36% at the national level. For many provinces, the efficiency can be as low as 15%. Main reasons for low efficiency are improper design of irrigation facilities, poor maintenance, careless operation, negligible water pricing as well as inefficient division of responsibilities among different agencies (Pazira and Sadeghzadeh, 1999; Khezarvarz et al., 2005). Efforts to increase the agricultural water use efficiency have been made through increasing crop water productivity (*CWP*) at plant and field levels. But this has not so far alleviated the water scarcity. In many areas, the situation has been worsening.

Iran currently has 19 million ha of agricultural land, accounting for 12% of the total area of the country. Of the total agricultural area, over 60% is devoted to wheat, 20% to barley, 5% to rice, 2% to maize and the rest of the area is covered by other crops. Cereals are the largest user of irrigation water. Of the total water diverted to irrigate cereal crops, wheat uses more than 70%. This amount of water demand exceeds the internal renewable water resources availability in many provinces located at central dry regions. Therefore a large amount of water is extracted from fossil ground water or water

transfer projects to meet the water demand.

As agriculture is the largest water user in most water scarce countries, the main focus of this study is on the impact of water management on agricultural and food security. Strategies and programs have been sought to produce more food with less water (Kijne et al., 2003; Bouman, 2007). Three key principles to enhance *CWP* have been proposed as the priority topics in the Challenge Program on Water and Food: i) effective development of genotypes to accelerate improvement of *CWP* at ‘plant level’, ii) new opportunities and technologies for integrated crop and natural resources management at ‘field and farm level’, and iii) opportunities to reallocate water from smaller-value to larger-value uses and to enhance water productivity at the ‘regional level’. One promising strategy is based on the concept of virtual water trade (VWT). The goal of this strategy is to balance the water budget and to improve water use efficiency at the regional level through adjusting cropping structure and interregional food trade (Yang et al., 2006). Virtual water refers to the water used in crop production. For instance, it takes about 1,300 cubic meters of water on average to produce one metric ton of wheat. But the exact value could vary greatly for different places depending on climatic conditions and agricultural practice. Hoekstra and Chapagain (2007) have defined the virtual water content of a product (a commodity, good or service) as the volume of freshwater used to produce the product, measured at the place where the product was actually produced. It refers to the sum of the water use in the various steps of the production chain. According to the concept of VWT water resources can be used more efficiently if crops are produced in the regions/provinces where water resources are abundant and crop water productivity of these crops is large and exported to the regions where water resources are scarce and crop water productivity is low. The concept has emerged in the mid 1990s (Allan, 1996) and thereafter draw much attention both in the political arena and scientific community. Most virtual water studies have been conducted at the level of international food trade. In contrast, there are only few studies concerning virtual water trade within countries (e.g. Novo et al., 2009; Verma et al., 2009). Despite the promising potential of VWT to alleviate water scarcity, the concept has generally not been well received in countries where water resources are scarce. At least three reasons have been given for this situation: a) lack of relevance of the global level studies to the solution of local water and food problems in the countries concerned; b) skepticism of water scarce countries to the reliance on food import; c) inadequate attention to the socio-economic factors and local specific conditions that are of importance in deciding on water, food and trade

policies of individual countries. In this situation, we believe that there is both a practical and scientific need to tackle the virtual water trade strategy (VWTS) at the country and sub-country level. Within a country, especially a large country such as Iran, natural conditions, including water endowments, can vary significantly across regions/provinces. This makes it possible to apply the VWTS within the country to alleviate regional/provinces water stress. More importantly, at the country and sub-country level, socio-economic factors as well as stakeholder interests and local specific conditions can be addressed more pertinently in the feasibility assessment of virtual water trade.

With this background the ultimate goal of this study is to develop a systematic framework for adjusting the structure of cropping pattern (ASCP) and the VWTS across regions/provinces taking Iran as a case study. For assessing the potential benefit of intra-county virtual water trade, however, a sound knowledge of crop water productivity (*CWP*) and water resources availability on relevant spatial and temporal scales is of importance (Yang and Zehnder, 2007). Developing models for the systematic assessment of water resources availability, agricultural water use, crop yield as well as *CWP* at high spatial and temporal resolution is useful for enhancing the understanding of water and food relations and for laying the basis for intra-country VWT assessment. To attain the main goal in this study we specified the following objectives:

1. Modeling water resources availability with a subbasin spatial and monthly temporal resolution, taking into account dam operations and irrigation practices;
2. Assessing the impact of climate change on water resources availability, including the role of floods and droughts;
3. Modeling crop yields, crop water consumption and crop water productivity;
4. Calibration, validation and uncertainty analysis of the combined hydrology-crop production model;
5. Using the calibrated model to analyze water demand and water supply and to perform scenario analysis of status quo agricultural water management and its policy implications;
6. Constructing a systematic framework to assess the provincial ASCP and cereal production corresponding to the VWTS taking into account constraints related to wheat self-sufficiency (as a stakeholder/government interest), land availability and water scarcity.

To achieve the objectives 1-3 of this study, we used the model Soil and Water assessment Tool (SWAT) (Arnold et al., 1998). SWAT is a semi-physical, semi-

distributed and GIS-coupled model, which is a computationally efficient simulator of hydrology and crop growth at various scales. 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, landuses, 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. The program has been successfully used in many international applications (Gassman et al., 2007).

Uncertainties inherent in the input data and parameters must be taken into account in the interpretation of the model output. To obtain the objectives 4-5, we used program SUFI-2 (Abbaspour *et al.*, 2007) for calibration and uncertainty analysis. SUFI-2 is a tool for sensitivity analysis, multi-site calibration, and uncertainty analysis. It is capable of simultaneously optimizing a large number of parameters and measured data from many gauging stations in an efficient way. To satisfy the last objective in this study we sought to formulate it as a multi-criteria analysis problem and solve by optimization method.

1.2 Contents and structure of the thesis

This thesis consists of four main chapters (chapter 2 to 5):

Chapter 2 describes how SWAT was used to estimate the internal renewable water availability (blue water and green water) in Iran at a sub-basin spatial scale and a monthly time step. The procedure included model setup, calibration, and validation, taking the reservoirs operations and irrigated wheat production into account, and quantification of the uncertainty in model outputs.

In **Chapter 3**, we analyzed the impact of future climate scenarios on the country's water resources. The selected scenarios were generated for periods of 2010-2040 and 2070-2100 using the Canadian Global Coupled Model (CGCM 3.1). The SWAT model in Chapter 2 was applied to different climate scenarios to predict the impact of future climate on precipitation, blue water, green water, and wheat yield across the country.

Chapter 4 describes the modeling of crop yield and *CWP* for wheat across the country. 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.

Chapter 5 presents how a systematic framework was constructed to assess the provincial ASCP and cereal production corresponding to the VWTS. The framework was used to analyze alternative scenarios to assess the optimal area of cereal crops across provinces to maximize national cereal production, while meeting a certain level of wheat self-sufficiency and water scarcity in individual provinces.

Finally in **Chapter 6**, general conclusions concerning the water and food management and planning in Iran and the countries with similar conditions are drawn. A number of shortcomings encountered in modeling the water and crop production are pointed out. Finally, an outlook is provided pointing out the potential applicability of the models developed in this study to include water quality, sediment, and other types of land uses in Iran and other countries with similar conditions.

References

- Abbaspour, K.C., 2007. User Manual for SWAT-CUP, SWAT Calibration and Uncertainty Analysis Programs. Swiss Federal Institute of Aquatic Science and Technology, Eawag, Duebendorf, Switzerland. 93 pp.
- Allan, J.A., 1996. Policy responses to the closure of water resources: regional and global issue. In: Howsam, P., Carter, R.C. (Eds), *Water Policy: Allocation and Management in practice*. Chapman and Hall, London.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment - Part 1: Model development. *Journal of American Water Resources*, 34 (1), 73-89.
- Bouman, B.A.M., 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales, *Agricultural Systems*, 9, 43–60.
- Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The soil and water assessment tool: historical development, applications, and future research directions, *Transaction of ASABE*, 50, 1211-1250.
- Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern, *Water Resources Management*, 21(1), 35–48.

- IPCC, 2001. *Climate change 2001: impacts, adaptation, and vulnerability* Cambridge University, Cambridge, United Kingdom.
- Keshavarz, A., Ashrafi, S., Hydari, N., Pouran, M., Farzaneh, E., 2005. Water allocation and pricing in agriculture of Iran, in *Water conservation, reuse, and recycling, Proceeding of an Iranian American workshop*, pp. 153-172, The National Academies Press: Washington, D.C.
- Kijne, J.W., Barker, R., Molden, D., 2003. *Water productivity in agriculture: limits and opportunities for improvement*, Comprehensive Assessment of Water Management in Agriculture Series 1. CAB7IWMI, Wallingford: Colombo.
- Novo, P., Garrido, A., Varela-Ortega, C., 2009. Are virtual water “flows” in Spanish grain trade consistent with relative water scarcity?, *Ecological Economics*, 68, 1454-1464.
- Qadir, M., Sharma, B.R., Bruggeman, A., Choukr-Allah, R., Karajeh, F., 2007. Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries, *Agricultural Water Management*, 87, 2-22.
- Pazira, E., Sadeghzadeh, K., 1999. Sustainable soil and water use in agricultural sector of Iran. In: *Proceedings of 99 international conference on agricultural engineering*, Beijing, China.
- Rosegrant, M.W., Cai, X., Cline, S.A., 2002. *World Water and Food to 2025: Dealing With Scarcity*. International Food Policy Research Institute, Washington, DC.
- Verma, S., Kampman, D.A., Zaag, P., Hoekstra, A.Y., 2009. Going against the flow: A critical analysis of inter-state virtual water trade in the context of India’s National River Linking Program, *Physics and Chemistry of the Earth*, 34, 261-269.
- Yang, H., Zehnder, A., 2007. “Virtual water”: An unfolding concept in integrated water resources management, *Water Resources Research*, 43, W12301.
- Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade, *Hydrology and Earth System Sciences*, 10, 443–454.

HYDROLOGICAL PROCESSES 23 (3): 486-501 2009**2 MODELLING BLUE AND GREEN WATER RESOURCES****AVAILABILITY IN IRAN**

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Abstract

An exact knowledge of the internal renewable water resources of a country is a strategic information which is needed for long term planning of a nation's water and food security, among many other needs. New modeling tools allow this quantification with high spatial and temporal resolution. In this study we used the program Soil and Water Assessment Tools (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.

Keywords: SWAT, SUFI-2, internal water resources availability, irrigated wheat yield, uncertainty analysis, large-scale hydrologic modeling.

2.1 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 to 2001 accounted for 80% of the country’s total domestic wheat supply, making Iran one the largest wheat importer 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 ground water resources on a regional scale for Iran. There is, however, a lack of information with adequate spatial and

temporal resolution concerning 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 modeling. Furthermore, irrigated agriculture, which uses more than 90% of total water withdrawal and more than 60% of total renewable water resources in the country (Keshavarz *et al.*, 2005; Alizadeh and Keshavarz, 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. Second, 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, 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. GEPIC (Liu *et al.*, 2007) addresses spatial variability of crop yield and evapotranspiration, but lacks an explicit component for large scale hydrology. SWIM (Krysanova *et al.*, 2005) was developed for use in mesoscale and large river basins ($> 100000 \text{ km}^2$) mainly for climate change and land use change impact studies, and 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 program SUFI-2 (Abbaspour *et al.*, 2007a). 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. In a study 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, and large-scale models. In addition, SUFI-2 is linked to SWAT (in the SWAT-CUP software, Abbaspour, 2007b) through an interface that includes also the programs GLUE (Beven and Binley, 1992), ParaSol (van Griensven and Meixner, 2006), and a Monte Carlo Markov Chain, MCMC, (Vrugt *et al.*, 2003) algorithm.

2.2 Material and methods

2.2.1 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.*, 2007a; 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 (ver. 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 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 modeling. 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 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 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).

2.2.2 Description of the study area

2.2.2.1 Climate and hydrology

Iran, with an area of 1,648,000 km² is located between 25 and 40 degrees north latitude and 44 to 63 degrees east longitude. 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 semiarid, Iran has a wide spectrum of climatic conditions. The average annual precipitation is 252 mm year⁻¹. The northern and high altitude areas found in the west receive about 1600-2000 mm year⁻¹ (NCCO 2003), while the central and eastern parts of the country receive less than 120 mm year⁻¹. The per capita freshwater availability for the country was estimated at around 2000 m³capita⁻¹year⁻¹ in the year 2000 and expected to go below 1500 m³capita⁻¹year⁻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 regions are delineated in Figure 2.1. Table 2.1 shows some pertinent characteristics of the eight hydrologic regions. Table 2.2 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 and 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 the country.

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

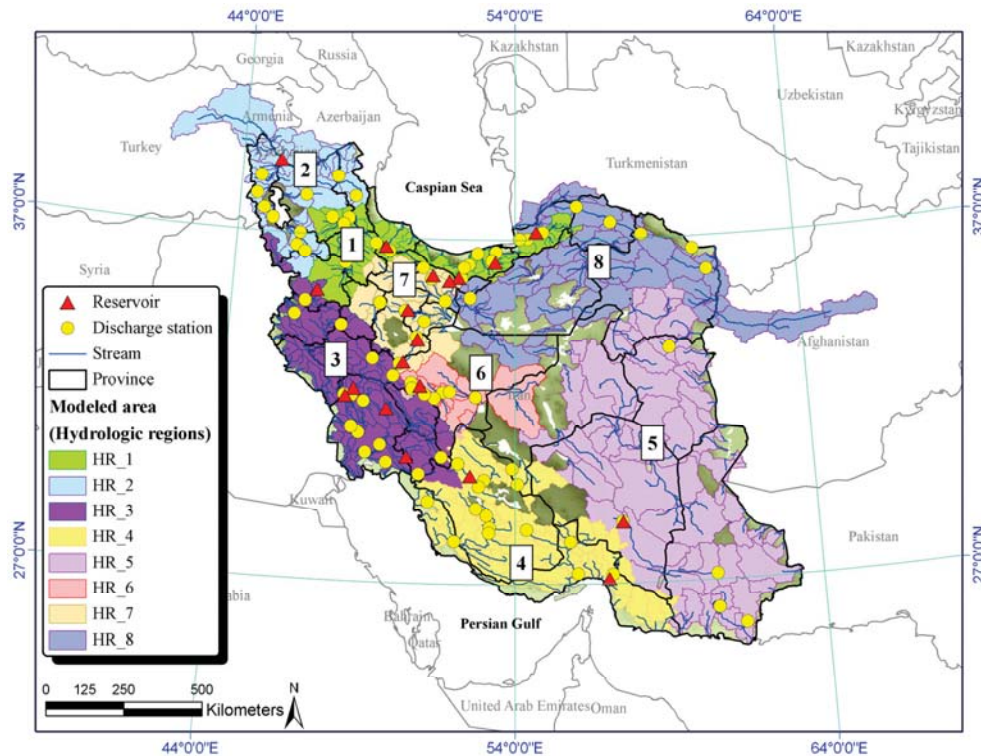


Figure 2.1 - Study area and the main hydrologic regions. The dark green areas in the background include wetlands, lakes, marshes, etc., which needed to be cut from the DEM in order to have a correct river pattern. They are not included in the model.

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, 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 $47.5 \text{ m}^3 \text{ s}^{-1}$ at the central plateau of Iran.

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.

Table 2.1- 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 | 97478 | 599 | 66 | - | - | 1.55 | 15.13 | 3.59 | 13.09 | 61.96 | 1.81 | 2.83 |
| HR 2 | 131973 | 399 | 58 | - | 14.20 | - | - | 11.30 | - | 54.22 | 17.53 | 2.61 |
| HR 3 | 185042 | 545 | 92 | 2.35 | 7.92 | - | - | 7.025 | - | 29.25 | - | 53.44 |
| HR 4 | 196329 | 278 | 87 | 25.27 | - | - | - | 1.77 | - | 1.77 | - | 71.18 |
| HR 5 | 459309 | 132 | 68 | 35.68 | 2.44 | 0.15 | 1.01 | 2.55 | 0.86 | 18.20 | 1.68 | 37.38 |
| HR 6 | 66654 | 152 | 26 | 65.28 | - | 0.13 | 0.40 | - | - | 7.08 | - | 27.08 |
| HR 7 | 82268 | 287 | 43 | 17.17 | - | - | - | - | - | 28.97 | - | 53.85 |
| HR 8 | 256553 | 197 | 67 | 27.48 | 0.99 | - | - | 1.08 | - | 18.21 | - | 52.22 |

^[a] Modeled 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 subbasin. 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: savanna, SAVA: grassland, SHRB: shrub land.

Table 2.2 - 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 (MCM) |
|------------------|--------------|--------------------|--------------------|-------------------|---------------------------------|----------------------|
| 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 | Gharechai | 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 | Shirin Rud | 1998 | 53.30 | 36.35 | 4.1 | 191 |
| Zayandeh Rud | Zayandeh Rud | 1970 | 50.74 | 32.74 | 48 | 1450 |

MCM: million cubic meter

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 Northeastern Iran and flows westward to end at the south-eastern 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 neighbor countries only the Hirmand river, located in HR5, was excluded from our modeling study, 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.

2.2.2.2 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 percent 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 ground water (Ardakanian, 2005). Owing 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 percolation. 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 modeling 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 SCI (1990-2002) the major irrigated areas are distributed across 11 provinces (Table 2.3). 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 other 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 2.3 - Proportion of irrigated areas under cultivation of wheat in different provinces

| 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 Balochestan | 50.82 |
| Tehran | 37.35 |
| Yazd | 37.47 |
| Zanjan | 65.96 |

AIW: average (1990-2002) annual area under cultivation of irrigated wheat;

TIA: total irrigated area

2.2.3 Model inputs and model setup

Data required for this study were compiled from different sources. They include: Digital Elevation Model (DEM) that was extracted from the Global U.S. Geological

Survey's (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>). The Soil map was 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, 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. Time spans 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 in 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 of 1977 to 2002. Historical records on annual yield and area cultivated with irrigated wheat were obtained for the period of 1990 to 2002 from the Agricultural Statistics and the Information Center of Ministry of Jahade-Agriculture and Statistical Center of Iran. A drainage area of 600 km² 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

km² the modeled area doesn't cover the entire land surface of the country, especially, the coastal regions and some desert areas having a watershed area of less than 600 km². In these cases the results were linearly extrapolated from the closest modeled 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, assuming that there is no water and fertilizer 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 from 1990-2002 considering 3 years as the warm-up period, and for validation from 1980-1989 also using 3 years as warm-up period. With the above specifications, a model run took about 15 minutes of execution time for each run in a 3 Ghz dual processor PC.

2.2.4 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.*, 2007a) and another 4 parameters related to crop growth (Ruget *et al.*, 2002; Ziaei and Sepaskhah, 2003; Wang *et al.*, 2005) were initially selected (Table 2.4). 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.*, 2007a; Schuol *et al.*, 2008b; Yang *et al.*, 2008), we used three different approaches here 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.

Table 2.4 - Initially selected input parameters in the calibration process

| Name ^[a] | Definition | <i>t</i> -value ^[b] | <i>p</i> -value ^[c] |
|---------------------|--|--------------------------------|--------------------------------|
| v__SURLAG.bsn | Surface runoff lag time (days) | 3.091 | 0.00211 |
| v__SMTMP.bsn | Snow melt base temperature (°C) | 6.448 | 2.76x10 ⁻¹⁰ |
| v__SFTMP.bsn | Snowfall temperature (°C) | 4.985 | 8.66E-07 |
| v__SMFMN.bsn | Minimum melt rate for snow during the year (mm/°C-day) | 2.95 | 0.00333 |
| v__TIMP.bsn | Snow pack temperature lag factor | 2.493 | 0.013 |
| v__SMFMX.bsn | Maximum melt rate for snow during the year (mm/°C-day) | 0.070 | 0.944 |
| r__CN2.mgt | SCS runoff curve number for moisture condition II | 19.801 | 2x10 ⁻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 | 3.20x10 ⁻⁷ |
| v__ESCO.hru | Soil evaporation compensation factor | 5.568 | 4.28x10 ⁻⁸ |
| v__EPCO.hru | Plant uptake compensation factor | 1.097 | 0.273 |
| r__OV_N.hru | Manning's n value for overland flow | 0.004 | 0.996 |
| r__SOL_K.sol | Soil conductivity (mm/hr) | 2.018 | 0.04414 |
| r__SOL_AWC.sol | Soil available water storage capacity (mm H ₂ O/mm soil) | 8.841 | 2x10 ⁻¹⁶ |
| r__SOL_BD.sol | Soil bulk density (g/cm ³) | 7.908 | 1.79x10 ⁻¹⁴ |
| 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) | 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__: The parameter value is replaced by given value or absolute change; r__: parameter value is multiplied by (1+ a given value) or relative change (See Abbaspour (2007b) for more detail).

^[b] *t*-value indicates parameter sensitivity. The large the *t*-value, the more sensitive the parameter

^[c] *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

The SUFI-2 (Abbaspour *et al.*, 2007a) 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., 2007a). 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-factor* \rightarrow 1) while having the narrowest band (*R-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):

$$\Phi = \begin{cases} |b|R^2 & \text{for } |b| \leq 1 \\ |b|^{-1} R^2 & \text{for } |b| > 1 \end{cases} \quad (1)$$

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:

$$g = \frac{1}{n} \sum_{i=1}^n \Phi_i, \quad (2)$$

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 modeled area. While in the regional approach, the function was optimized using the number of stations that fell in each of the eight hydrologic regions (Table 2.5).

Table 2.5 - Calibration performances of regional approach procedure

| Hydrologic region | Number of stations | Regional approach | | |
|-------------------|--------------------|-------------------|-----------------|-----------------|
| | | Goal function | <i>P-factor</i> | <i>R-factor</i> |
| 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 |

2.3 Results and discussion

2.3.1 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 2.4 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 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. Also in this study, where only SUFI-2 was used with 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 than with the other two approaches.

Table 2.5 presents the calibration results for the regional approach. On average, 53 percent of the data from 81 discharge stations fell within the 95PPU. The R -factor was 1.52. Figure 2.2 shows the coefficient of determination (R^2) for the individual discharge stations across the country. Most of the stations in HR6, HR3, and HR4 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).

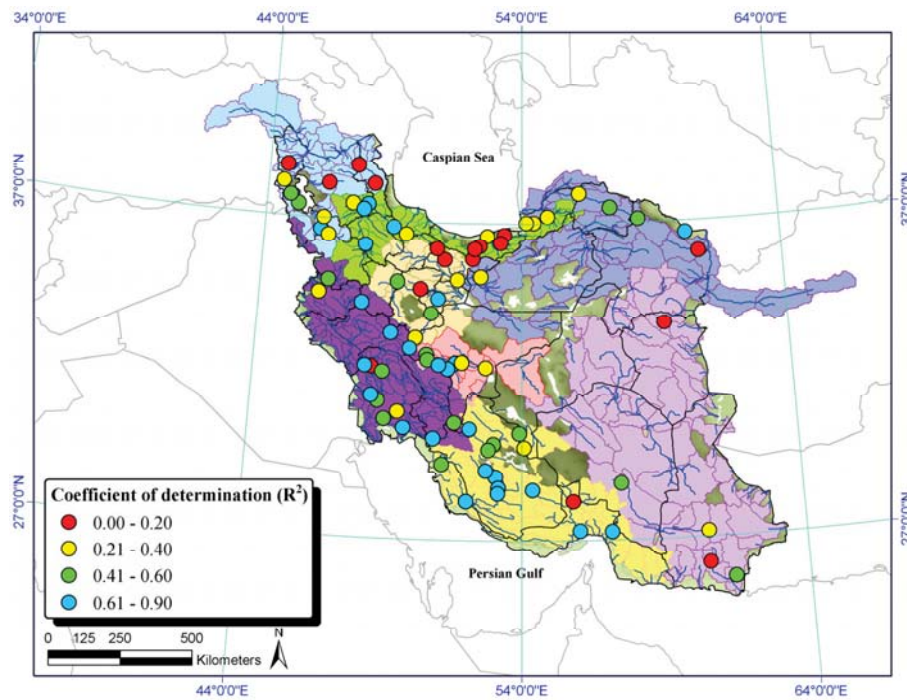


Figure 2.2 - Comparison of observed and simulated discharges using coefficient of determination (R^2) for 81 stations across the country resulting from the regional approach calibration procedure.

We constructed a “water management map” for the country for the period of study as illustrated in Figure 2.3. This management map shows the spatial distribution of some of the man’s activities influencing natural hydrology during the period of study. Regions with the highest activities have the worst calibration/validation results (compare

with Fig. 2.2) 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 modeling. As the extent of management in water resources development increases, hydrological modeling will become more and more difficult and will depend on the availability of detailed knowledge of the management operations.

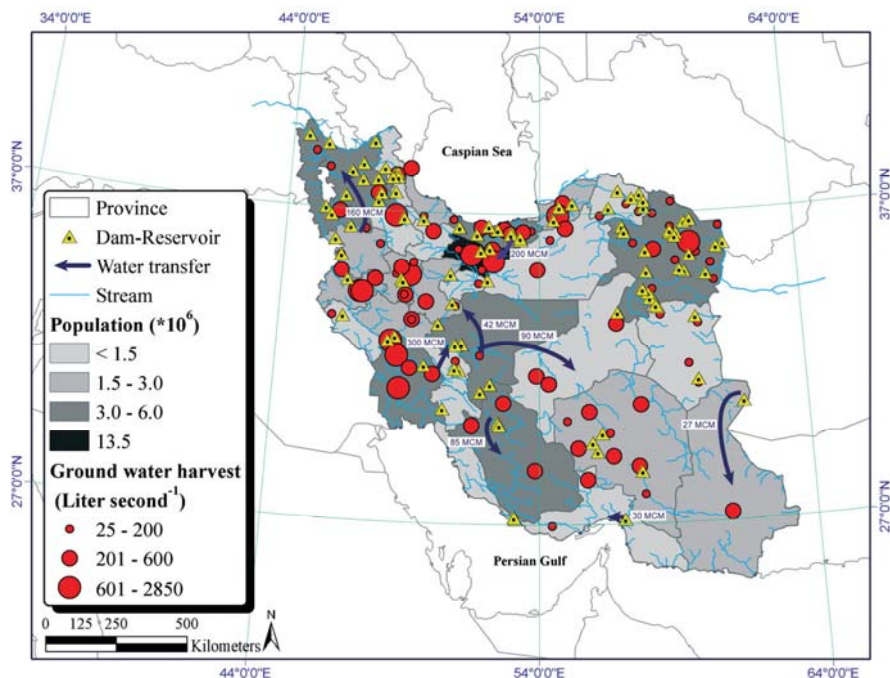


Figure 2.3 - Water management map of the country showing some of the man's activities during the period of study. The map shows locations of dams, reservoirs, water transfers, and ground water harvest. Map's background shows Provincial-based population.

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.* (2007a) 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 (FAO, 1986; Jensen, 1968), 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 2.4 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 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, that is the sum of river discharge and deep aquifer recharge.

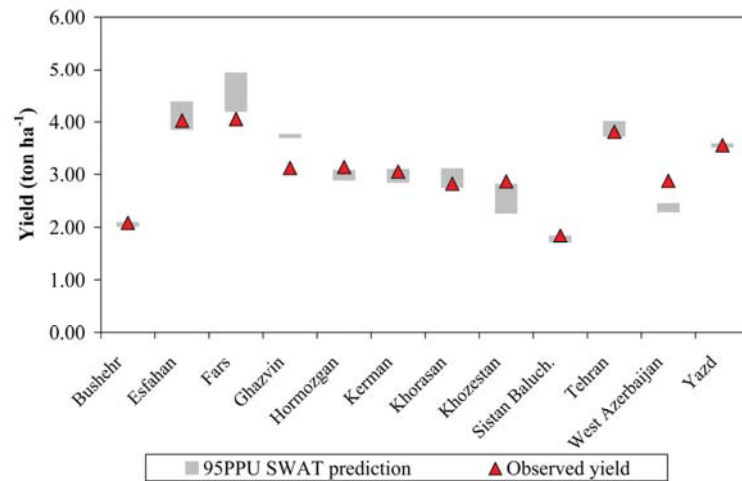


Figure 2.4 - Comparison of observed and simulated (expressed as 95% prediction uncertainty band) annual wheat yield averaged over the years 1990-2002 for different provinces.

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 2.5, 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.

2.3.2 Quantification of water resources

Monthly averages of internal renewable blue water resources (IRWR, the summation of water yield and deep aquifer recharge) were calculated for all of 506 sub-basins included in the model. Furthermore, the monthly IRWR of sub-basins were

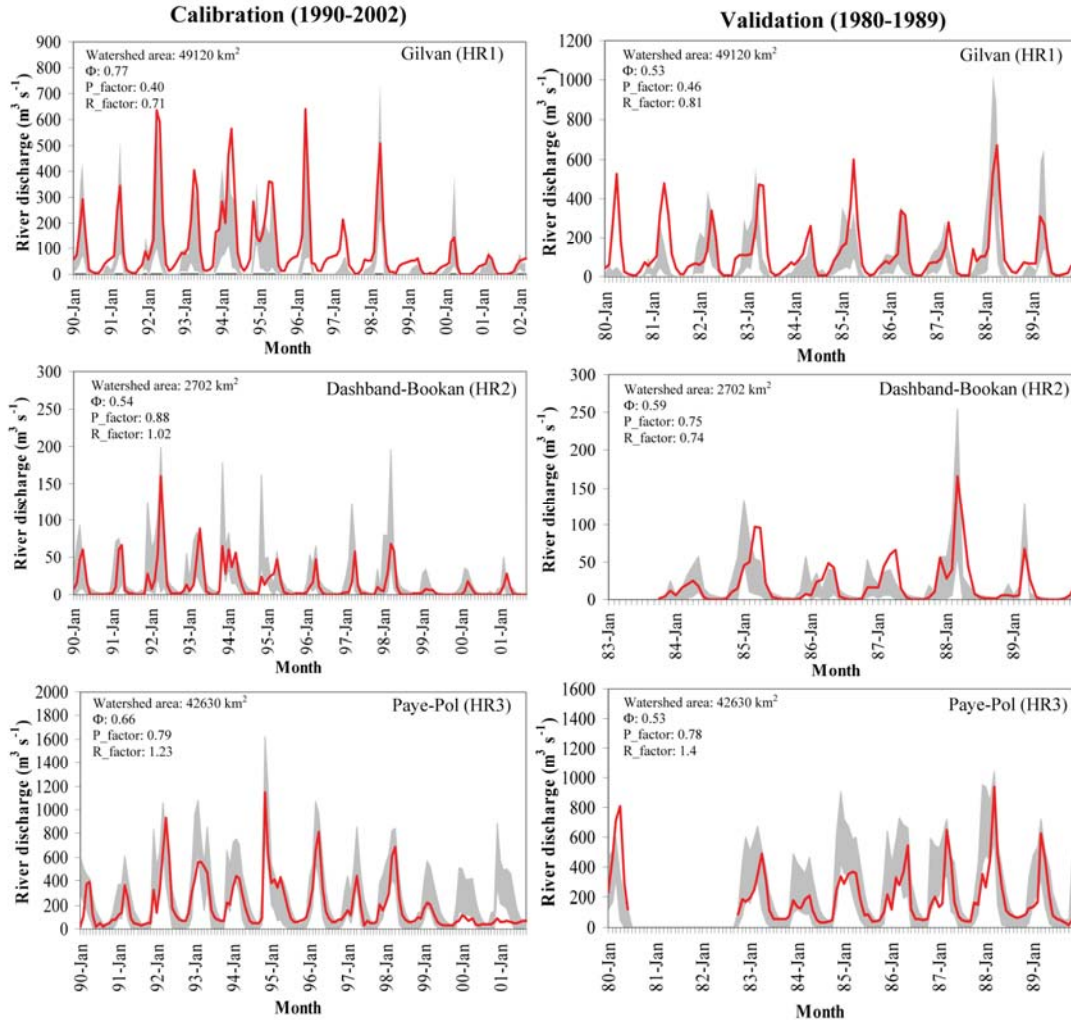


Figure 2.5 - Comparison of the observed (red line) and simulated (expressed as 95% prediction uncertainty band) discharges for three hydrometric stations located in hydrologic regions HR1, HR2, and HR3. Calibration (left) and validation (right) results are shown.

aggregated to estimate the regional, provincial and national IRWR availability. Figure 2.6 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.*, 2004). 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 ground water flow generated from precipitation. As shown in Figure 2.6, 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 (Fig. 2.4) and IRWR fall

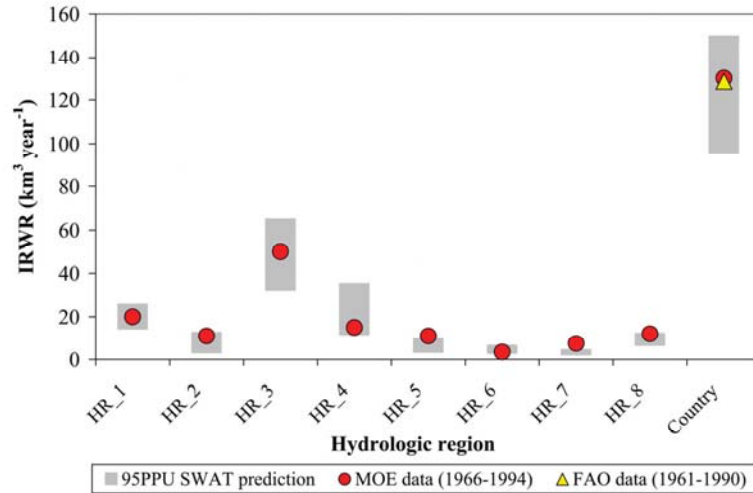


Figure 2.6 - Comparison of simulated average (1990-2002) annual regional internal renewable blue water resources (IRWR) with the available data from the Ministry of Energy (MOE) and FAO for the entire country.

within the uncertainty band of model prediction. Figure 2.7 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 2.7 and the “water management map” in Figure 2.3 shows the correspondence between high uncertainty provinces and the ones with substantial managements. It should be noted that the reported uncertainty includes both modeling 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 (personal 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

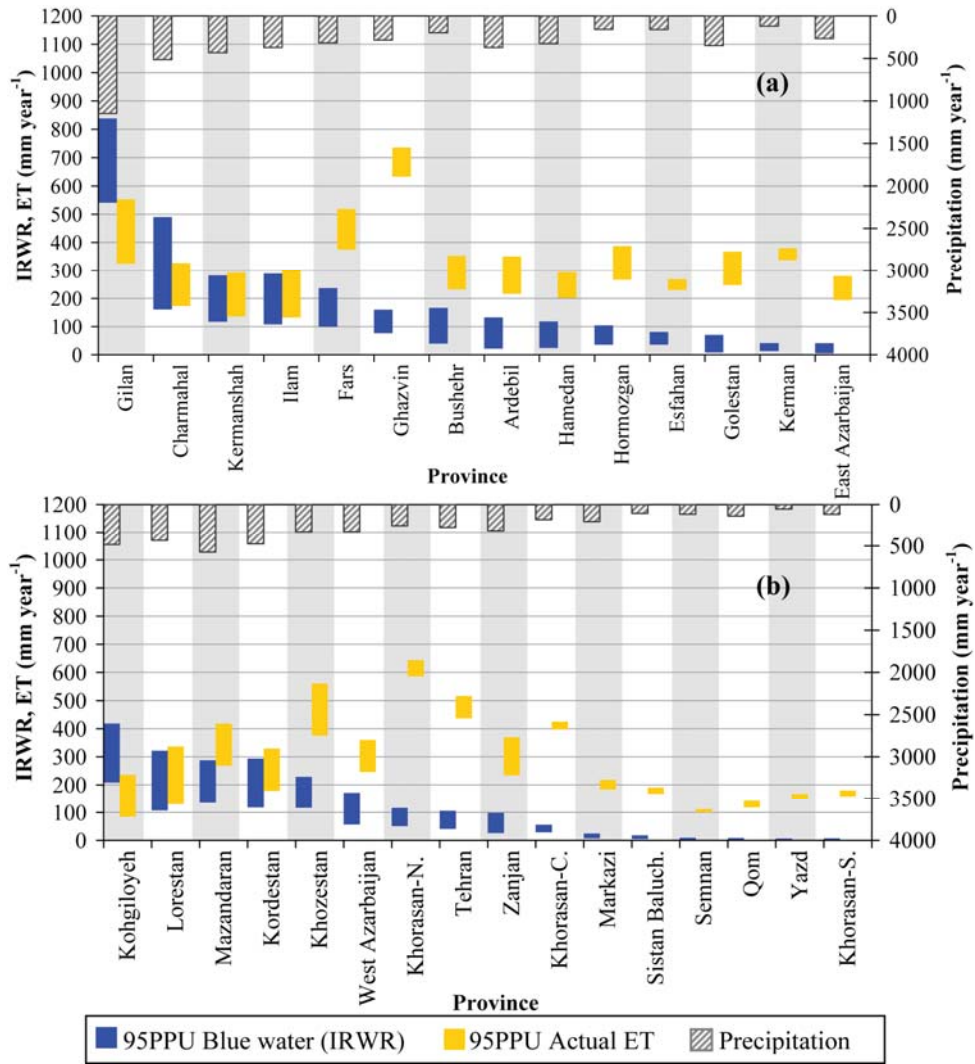


Figure 2.7 - Modelled average (1990-2002) annual provincial internal renewable blue water resources (IRWR), actual evapotranspiration (ET) expressed as 95% prediction uncertainty, and precipitation.

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 2.8 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

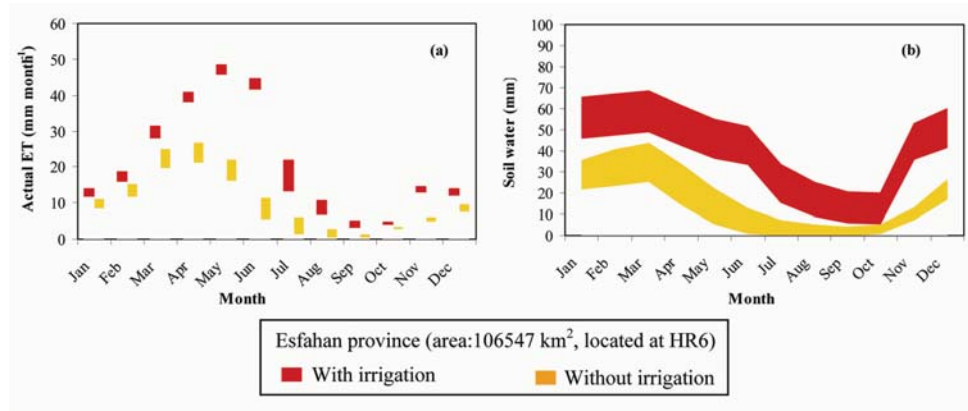


Figure 2.8 - Illustration of the differences in predicted actual ET and soil moisture with and without considering irrigation in Esfahan province. The variables are monthly averages for the period of 1990-2002.

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 2.8.

For a general overview of the hydrological components in the country at sub-basin level we constructed Figure 2.9. The average of the 95PPU interval for the 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 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 2.9 shows areas where rainfed 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 follow and presented in Figure 2.10:

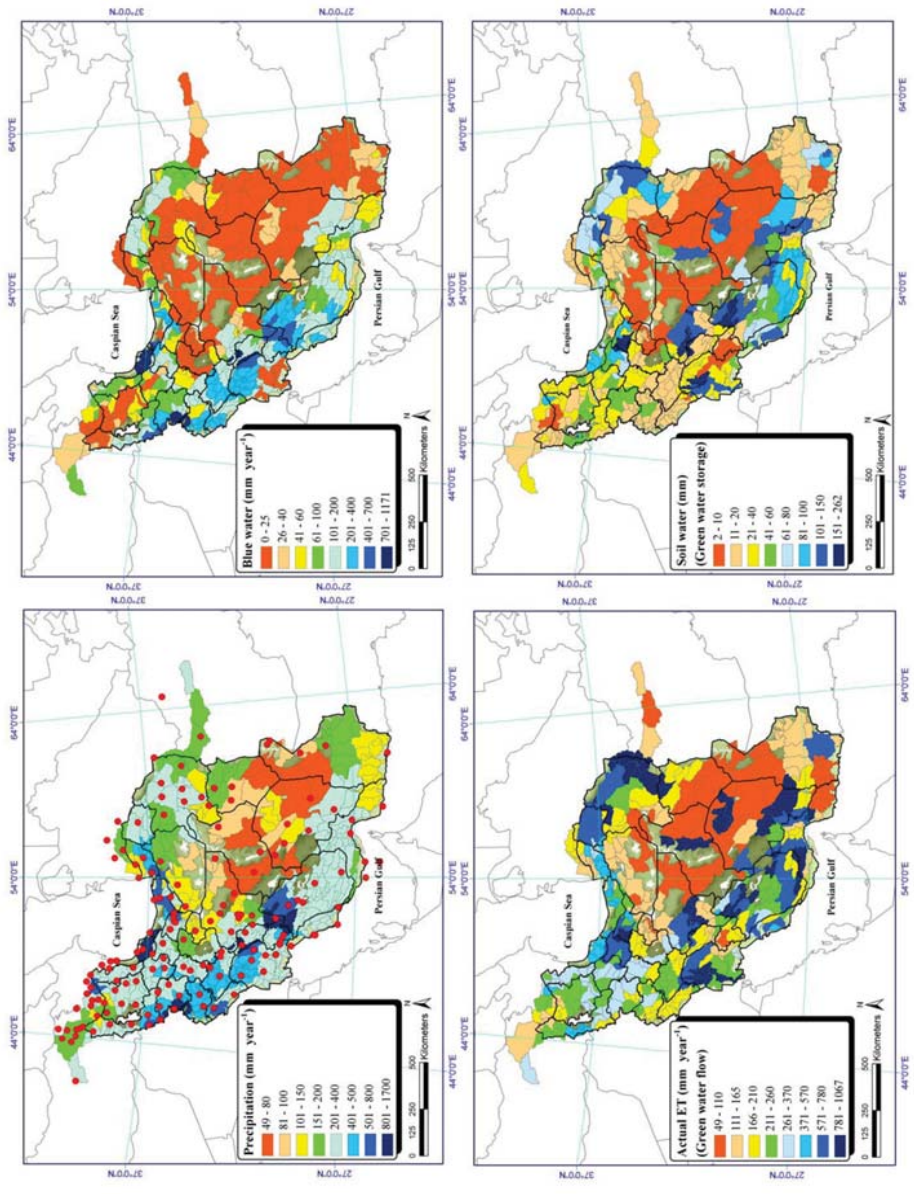


Figure 2.9 - Average (1990-2002) simulated annual precipitation, internal renewable blue water resources (IRWR), actual evapotranspiration (ET), and soil water at sub-basin level for the entire country.

$$CV = \frac{\sigma}{\mu} \times 100 \quad (3)$$

where σ is the standard deviation and μ is the mean of annual IRWR values for each subbasin. 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 rainfed agriculture. Figure 2.10 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.

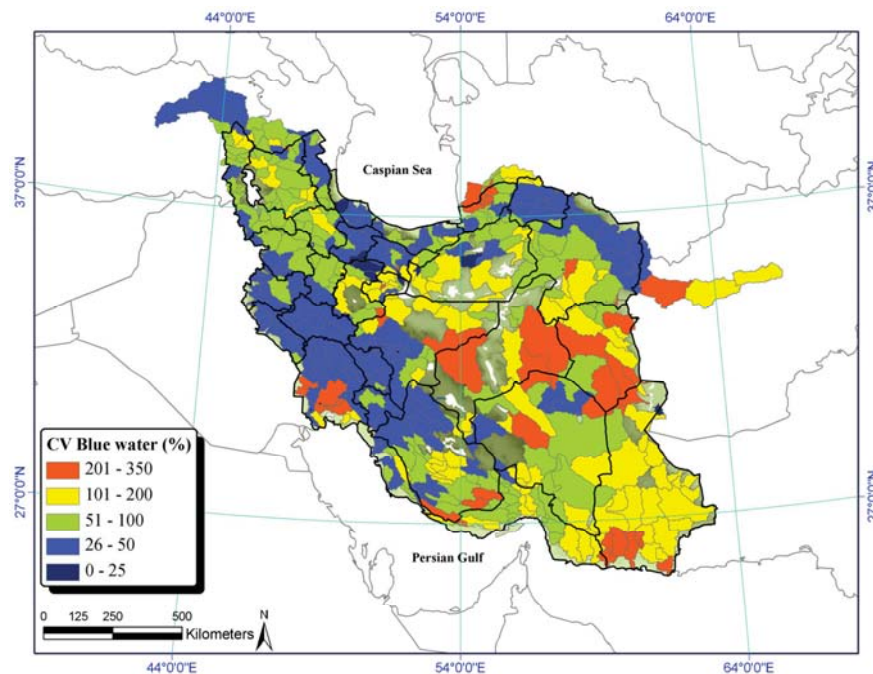


Figure 2.10 - Coefficient of variation (CV) of the modelled annual (1990-2002) internal renewable blue water.

To highlight the country's water scarcity situation, we plotted in Figure 2.11 the per capita internal renewable blue water availability in every sub-basin. For this we used a 2.5-arcminute population map available from the Center for International Earth Science Information Network's 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 m³ per capita based on the population estimate in 2005.

The spatial distribution of water resources availability in Figure 2.11, 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 m³ 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 arc-minutes 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 importance to balance water budgets in water scarce regions and to improve the efficiency of water resources utilization.

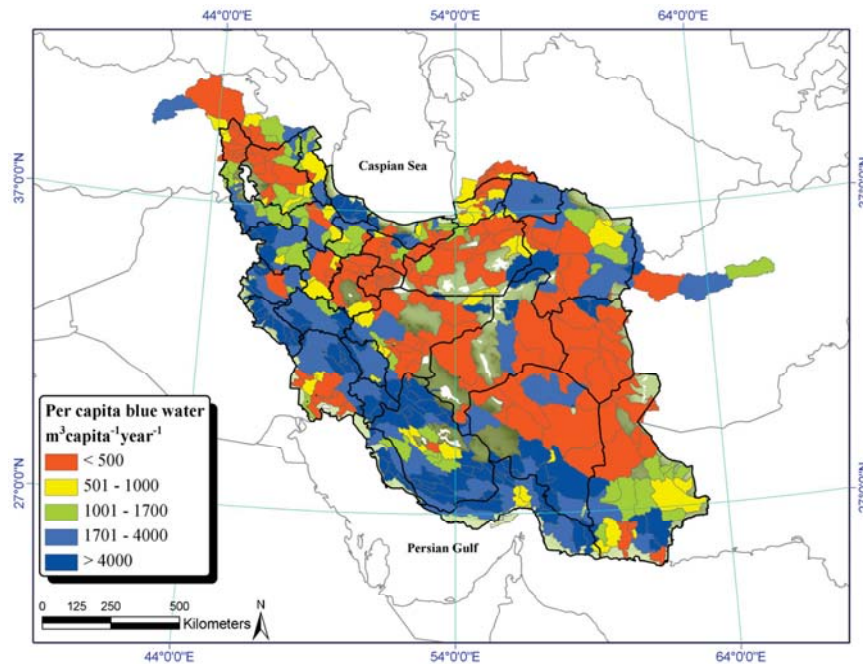


Figure 2.11 - Per capita blue water availability at 506 modelled sub-basins. Values of <500 indicate severe water stress, <1000 are high water stress, 1700 is water stress threshold, and >1700 indicates adequate water availability.

2.4 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, validation, as well as sensitivity and uncertainty analysis 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, with the current study, scenario analysis could be used 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 modeling 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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References

- Abbaspour KC, Sonnleitner MA, Schulin R. 1999. Uncertainty in estimation of soil hydraulic parameters by inverse modelling: Example lysimeter experiments. *Soil Sci. Soc. Am. J.* **63**: 501-509.
- Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R. 2007a. Modelling hydrology and water quality in the pre-Alpine/Alpine Thur watershed using SWAT. *Journal of Hydrology* **333**: 413-430. doi:10.1016/j.jhydrol.2006.09.014.
- Abbaspour KC. 2007b. User Manual for SWAT-CUP, SWAT Calibration and Uncertainty Analysis Programs. Swiss Federal Institute of Aquatic Science and Technology, Eawag, Duebendorf, Switzerland. 93 pp.
http://www.eawag.ch/organisation/abteilungen/siam/software/swat/index_EN. Date last accessed, August 2008.
- Abrishamchi A, Tajrishi M. 2005. Interbasin water transfer in Iran. In *Water conservation, reuse, and recycling: proceeding of an Iranian American workshop*, The National Academies Press: Washington, D.C.; 252-271.
- Akbari M, Toomanian N, Droogers P, Bastiaanssen W, Gieske A. 2007. Monitoring irrigation performance in Esfahan, Iran, using NOAA satellite imagery. *Agricultural Water Management* **88**: 99-109. doi:10.1016/j.agwat.2006.10.019.
- Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rosch T, Siebert S. 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **48**: 317-337. DOI: 10.1623/hysj.48.3.317.45290.
- Alizadeh A, Keshavarz A. 2005. Status of agricultural water use in Iran. In *Water conservation, reuse, and recycling: proceeding of an Iranian American*

- workshop*, The National Academies Press: Washington, D.C.; 94-105.
- Allan JA. 1997. 'Virtual Water': A Long Term Solution for Water Short Middle Eastern Economies?' *Occasional Paper. SOAS Water Issues Group*, King's College. UK.
- Ardakanian R. 2005. Overview of water management in Iran. In *Water conservation, reuse, and recycling: proceeding of an Iranian American workshop*, The National Academies Press: Washington, D.C.; 18-33.
- Arnold JG, Allen PM. 1996. Estimating hydrologic budgets for three Illinois watersheds. *Journal of Hydrology* **176**: 57-77.
- Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large area hydrologic modeling and assessment - Part 1: Model development. *Journal of the American Water Resources Association* **34**: 73-89.
- Banaei MH, Moameni A, Bybordi M, Malakouti MJ. 2005. *The soils of Iran: new achievements in perception, management and use*. Soil and Water Research Institute: Tehran; 481 p.
- Beven K, Binley A. 1992. The future of distributed models - model calibration and uncertainty prediction. *Hydrological Process* **6**: 279-298.
- Bouman BAM. 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agricultural Systems* **9**: 43-60. doi:10.1016/j.agry.2006.04.004.
- Chavoshian SA, Takeuchi K, Funada S. 2005. An overview to transboundary and shared water resources management in Iran, technical challenges and solutions. In *Role of Water Sciences in Transboundary River Basin Management*, Thailand; 189-195.
- Confalonieri R, Bocchi S. 2005. Evaluation of CropSyst for simulating the yield of flooded rice in northern Italy. *European Journal of Agronomy* **23**: 315-326. DOI:10.1016/j.eja.2004.12.002.
- Cosgrove WJ, Rijsberman FR. 2000. *World Water Vision*. Earthscan Publications: London.
- Döll P, Kaspar F, Lehner B. 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology* **270**: 105-134. doi:10.1016/S0022-1694(02)00283-4.
- Ehsani M. 2005. A vision on water resources situation, irrigation and agricultural production in Iran. In *ICID 21st European Regional Conference on Integrated Land and Water Management: Towards Sustainable Rural Development*,

- Frankfurt, Germany.
- Falkenmark M, Rockstrom J. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of Water Resources Planning and Management-ASCE* **132**: 129-132. doi:10.1061/(ASCE)0733-9496(2006)132:3(129).
- Falkenmark M, Lundquist J, Widstrand C. 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. *Natural Resources Forum* **13**: 258-267.
- Food and Agriculture Organization 1995. *The digital soil map of the world and derived soil properties*. CD-ROM, Version 3.5, Rome.
- Food and Agriculture Organization 2003. *Review of the world water resources by country*. Water Report Nr. 23: Rome.
- Food and Agriculture Organization 1986. Yield response to water. *Irrigation and Drainage Paper* **33**. FAO, Rom, Italy.
- Food and Agriculture Organization 2005. FAO statistical database. Food and Agriculture Organization of the United Nations. Available on the World Wide Web: <http://faostat.fao.org/>.
- Foy JK, Teague WR, Hanson JD. 1999. Evaluation of the upgraded SPUR model (SPUR2.4). *Ecological Modelling* **118**: 149-165. doi:10.1016/S0304-3800(99)00016-2.
- Gosain AK, Rao S, Basuray D. 2006. Climate change impact assessment on hydrology of Indian river basins. *Current Science* **90**: 346-353.
- Hargreaves GL, Hargreaves GH, Riley JP. 1985. Agricultural benefits for Senegal River Basin. *Journal of Irrigation and Drainage Engineering-ASCE* **111**: 113-124.
- Holvoet K, van Griensven A, Seuntjens P, Vanrolleghem PA. 2005. Sensitivity analysis for hydrology and pesticide supply towards the river in SWAT. *Physics and Chemistry of the Earth* **30**: 518-526. doi:10.1016/j.pce.2005.07.006.
- Jensen ME. 1968. Water consumption by agricultural plants. In *Water Deficits in Plant Growth (1)*. Academic Press: New York; 1-22.
- Keshavarz A, Ashrafi SH, Hydari N, Pouran M, Farzaneh EA. 2005. Water allocation and pricing in agriculture of Iran. In *Water conservation, reuse, and recycling: proceeding of an Iranian American workshop*, The National Academies Press: Washington, D.C.; 153-172.
- Kijne JW, Barker R, Molden D. 2003. Water productivity in agriculture: limits and

- opportunities for improvement. *Comprehensive Assessment of Water Management in Agriculture Series 1*. CAB7IWMI, Wallingford: Colombo.
- Krause P, Boyle DP, Bäse F. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advanced Geosciences* **5**: 89-97.
- Krysanova V, Hattermann F, Wechsung F. 2005. Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. *Hydrological Processes* **19**: 763-783. DOI: 10.1002/hyp.5619.
- Leff B, Ramankutty N, Foley JA. 2004. Geographic distribution of major crops across the world. *Global Biogeochemical Cycles* **18**: GB1009. DOI: 10.1029/2003GB002108, 2004.
- Lenhart T, Eckhardt K, Fohrer N, Frede HG. 2002. Comparison of two different approaches of sensitivity analysis. *Physics and Chemistry of the Earth* **27**: 645-654. doi:10.1016/S1474-7065(02)00049-9.
- Liu J, Williams JR, Zehnder AJB, Yang H. 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. *Agricultural Systems* **94**: 478-493. DOI: 10.1016/j.agsy.2006.11.019.
- Ministry of Energy of Iran. 1998. *An Overview of National Water Planning of Iran*. Tehran, Iran (available in Persian).
- Muleta MK, Nicklow JW. 2005. Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. *Journal of Hydrology* **306**: 127-145. DOI:10.1016/j.jhydrol.2004.09.005.
- Narasimhan B, Srinivasan R, Arnold JG, Di Luzio M. 2005. Estimation of long-term soil moisture using a distributed parameter hydrologic model and verification using remotely sensed data. *Transactions of the ASAE* **48**: 1101-1113.
- NCCO. 2003. Initial National Communication to United Nations Framework Convention on Climate Change. Published by Iranian National Climate Change Office at Department of Environment, Tehran, Iran.
- Neitsch SL, Arnold JG, Kiniry JR, Williams JR, King KW. 2002. *Soil and water assessment tool*. Theoretical documentation: Version 2000. TWRI TR-191. College Station, Texas: Texas Water Resources Institute.
- Oki T, Kanae S. 2006. Global hydrological cycles and world water resources. *Science* **313**: 1068-1072. DOI: 10.1126/science.1128845.
- Olivera F, Valenzuela M, Srinivasan R, Choi J, Cho HD, Koka S, Agrawal A. 2006. ArcGIS-SWAT: A geodata model and GIS interface for SWAT. *Journal of the*

- American Water Resources Association* **42**: 295-309.
- Postel SL, Daily GC, Ehrlich PR. 1996. Human appropriation of renewable freshwater. *Science* **271**: 785-788.
- Revenga C, Brunner J, Henninger N, Kassem K, Payne R. 2000. *Pilot analysis of global ecosystems: Freshwater systems*. World Resources Institute: Washington DC, USA.
- Rijsberman FR. 2006. Water scarcity: Fact or fiction? *Agricultural Water Management* **80**: 5-22. DOI:10.1016/j.agwat.2005.07.001
- Ritchie JT. 1972. A model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research* **8**: 1204-1213.
- Ruget F, Brisson N, Delecolle R, Faiver R. 2002. Sensitivity analysis of a crop simulation model, STICS, in order to choose the main parameters to be estimated. *Agronomie* **22**: 133-158.
- Schuol J, Abbaspour KC, Sarinivasan R, Yang H. 2008a. Estimation of freshwater availability in the West African Sub-continent using the SWAT hydrologic model. *Journal of Hydrology*. **352**: 30-42.
- Schuol J, Abbaspour KC, Yang H, Srinivasan R, Zehnder AJB. 2008b. Modelling blue and green water availability in Africa. *Water Resources Research*. doi:10.1029/2007WR006609, in press.
- Sharpley AN, Williams JR. 1990. *EPIC-Erosion Productivity Impact Calculator: 1. model documentation*. U.S. Department of Agriculture, Agricultural Research Service, Tech. Bull. 1768.
- Siebert S, Döll P, Feick S, Hoogeveen J, Frenken K. 2007. *Global Map of Irrigation Areas version 4.0.1*. Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy.
- SCI (Statistical Center of Iran) 1990-2002. Statistical year books of Iran, Tehran, Iran.
- Thoms MC, Sheldon F. 2000. Water resource development and hydrological change in a large dryland river: the Barwon-Darling River, Australia. *Journal of Hydrology* **228**: 10-21. doi:10.1016/S0022-1694(99)00191-2.
- USDA 2003. *Production Estimates and Crop Assessment Division*, Foreign Agricultural Service.
http://www.fas.usda.gov/pecad2/highlights/2003/12/iran_dec2003/index.htm
- USGS. 1993. *Digital elevation model guide*. Washington, D.C.: U.S. Geological Survey.

- Available at: <http://edc.usgs.gov/guides/dem.html>. Accessed 15 March 2005.
- van Griensven A, Meixner T. 2006. Methods to quantify and identify the sources of uncertainty for river basin water quality models. *Water Science and Technology* **53**: 51-59.
- Vörösmarty CJ, Green P, Salisbury J, Lammers RB. 2000. Global water resources: vulnerability from climate change and population growth. *Science* **289**: 284-288. DOI: 10.1126/science.289.5477.284.
- Vrugt JA, Gupta HV, Bouten W, Sorooshian S. 2003. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. *Water Resources Research* **39**, art. no. 1201. DOI:10.1029/2002WR001642.
- Wang X, Williams JR, Izaurrealde RC, Atwood JD. 2005. Sensitivity and uncertainty analysis of crop yields and soil organic carbon simulated with EPIC. *Transactions of the ASAE* **48**:1041-1054.
- White KL, Chaubey I. 2005. Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model. *Journal of the American Water Resources Association* **41**: 1077-1089. DOI:10.1111/j.1752-1688.2005.tb03786.x
- Yang H, Reichert P, Abbaspour KC, Zehnder AJB. 2003. A water resources threshold and its implications for food security. *Environmental Science and Technology* **37**: 3048-3054.
- Yang, H., L. Wang, A.J.B. Zehnder, and K. C. Abbaspour, 2006. Virtual Water Trade: an assessment of water use efficiency in the international food trade. *Journal of Hydrology and Earth System Sciences*, 10, 443-454.
- Yang J, Reichert P, Abbaspour KC, Yang H. 2007. Hydrological modelling of the Chaohe basin in China: Statistical model formulation and Bayesian inference. *Journal of Hydrology* **340**: 167-182. doi:10.1016/j.jhydrol.2007.04.006.
- Yang J, Reichert P, Abbaspour KC, Yang H. 2008. Comparing uncertainty analysis techniques for a SWAT application to Chaohe Basin in China. *Journal of Hydrology* **358**: 1-23.
- Ziaei A, Sepaskhah AR. 2003. Model for simulation of winter wheat yield under dryland and irrigated conditions. *Agricultural Water Management* **58**: 1-17.

WATER RESOURCES RESEARCH 45: W10434 2009**3 ASSESSING THE IMPACT OF CLIMATE CHANGE ON
WATER RESOURCES OF IRAN**

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Abstract

As water resources become further stressed due to increasing levels of societal demand, understanding the effect of climate change on various components of the water cycle is of strategic importance in management of this essential resource. In this study, we used a hydrologic model of Iran to study the impact of future climate on the country's water resources. The hydrologic model was created using the SWAT model (Soil and Water Assessment Tool) and calibrated for the period from 1980 to 2002 using daily river discharges and annual wheat yield data at a subbasin level. Future climate scenarios for periods of 2010-2040 and 2070-2100 were generated from the Canadian Global Coupled Model (CGCM 3.1) for scenarios A1B, B1 and A2, which were downscaled for 37 climate stations across the country. The hydrologic model was then applied to these periods to analyze the effect of future climate on precipitation, blue water, green water, and yield of wheat across the country. For future scenarios we found that in general, wet regions of the country will receive more rainfall while dry regions will receive less. Analysis of daily rainfall intensities indicated more frequent and larger intensity floods in the wet regions and more prolonged droughts in the dry regions. When aggregated to provincial levels, the differences in the predictions due to the three future scenarios were smaller than the uncertainty in the hydrologic model. However, at the subbasin level the three climate scenarios produced quite different results in the dry regions of the country, although the results in the wet regions were more or less similar.

Keywords: Hydrologic modeling, CGCM, blue water, green water, SWAT.

3.1 Introduction

Nearly all regions of the world are expected to experience a net negative impact of climate change on water resources and freshwater ecosystems [IPCC, 2007]. The intensity and characteristics of the impact, however, can vary significantly from region to region. Some regions are likely to experience water shortages. Coupled with increasing demand, this is likely to result in large increases in the number of people at risk of water scarcity. Rising sea levels in heavily-populated coastal regions, on the other hand, may threaten the lives and livelihood of millions of people. The frequency of floods and droughts are certain to increase in much of the world. The economic cost is likely to be high and the overall crop yield may decline, increasing the risk of poverty and hunger. For a long-term strategic planning of a country's water resources in the face of the evolving climate change impacts, it is important that these effects be quantified with a high spatial and temporal resolution.

A large number of publications in the literature deal with a particular component of water balance, e.g., stream flow [Fu *et al.*, 2007; Caballero *et al.*, 2007], groundwater recharge [Scibek and Allen, 2006; Jyrkama and Sykes, 2007], runoff [Nunes *et al.*, 2009], evapotranspiration [Calanca *et al.*, 2006] or a particular event throughout a year, e.g., low flows, peak flows [Cuo *et al.*, 2009], extreme events [Xiong *et al.*, 2009], and changes or shifts in seasonal processes [Thomas *et al.*, 2007]. However, fewer publications have focused on the long term evaluation of a basin's water balance due to climate change impacts on regional hydrologic processes. Yet this may be the most beneficial application of hydro-climatology to support long-term water resources management and planning [Serrat-Capdevila *et al.*, 2007]. An integrated hydrological simulation model could help to study the net effect of climate change in a given region.

In this paper, we report on the results of investigating the impact of climate change on water resources in Iran for the near (2010-2040) and far (2070-2100) future. Iran is a country of large climatic variability from north to south. The northern part of the country is quite wet with frequent costly floods, while the southern part is dry with large water scarcity, frequent droughts, and a large reliance on dwindling groundwater resources. To get an overall picture, we used the integrated hydrological model "Soil and Water Assessment Tool" (SWAT) [Arnold *et al.*, 1998] to study the effect of climate change at a subbasin level at a monthly time step for the whole country. We specifically looked at the changes in various components of the water balance including precipitation

and evapotranspiration distribution, river discharge, soil moisture, and aquifer recharge. These variables were then used to quantify the changes in water resources with respect to blue water (river discharge plus aquifer recharge) and green water (soil moisture and evapotranspiration). The results will contribute to the scientific community's understanding of climate change impacts on water resources and provide information to support future water resources planning and management in Iran and other countries with the same climatic conditions.

We used a calibrated SWAT model of Iran in this study based on modifications of the model developed originally by *Faramarzi et al.* [2009]. This model consisted of parameters that were expressed probabilistically, reflecting the combined uncertainties of input, model structure, and parameters. The impact on various components of the water resources of the country were quantified at the subbasin scale using a series of anomaly maps (% deviations from historic data). In addition, the impact of climate change on flooding and droughts as well as wheat yield were also investigated. The implications of these impacts for the water and food security of the country are addressed at the final section of this paper.

3.2 Materials and methods

3.2.1 Description of the study area

Iran is located between 25 and 40 degrees north latitude and 44 to 63 degrees east longitude and has a total area of 1,648,000 km² (Figure 3.1). The altitude varies from -40 m to 5670 m, which has a pronounced influence on the diversity of the climate. Iran as a whole is a semi-arid country. The per capita freshwater availability for the country was estimated to be around 2000 m³ capita⁻¹ year⁻¹ in the year 2000 by Yang et al. [2003] who also predicted that it may go below 1500 m³ capita⁻¹ year⁻¹ by 2030 due to the population growth. However, Iran has a broad spectrum of climatic conditions across regions with significant rainfall variability (averages of 2000 mm year⁻¹ in the northern and western provinces, and 120 mm year⁻¹ in the central and eastern parts of the country) and temperature variability (extremes of -20 °C in the south-west to 50 °C along the Persian Gulf). Climate change is expected to have different impacts on rainfall and temperature patterns across regions, and consequently, on the spatial and temporal distributions of the various components of water resources. More details of the study area can be found in *Faramarzi et al.* [2009].

Roughly 37 million hectares of Iran's total surface area is arable land. Of this, 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

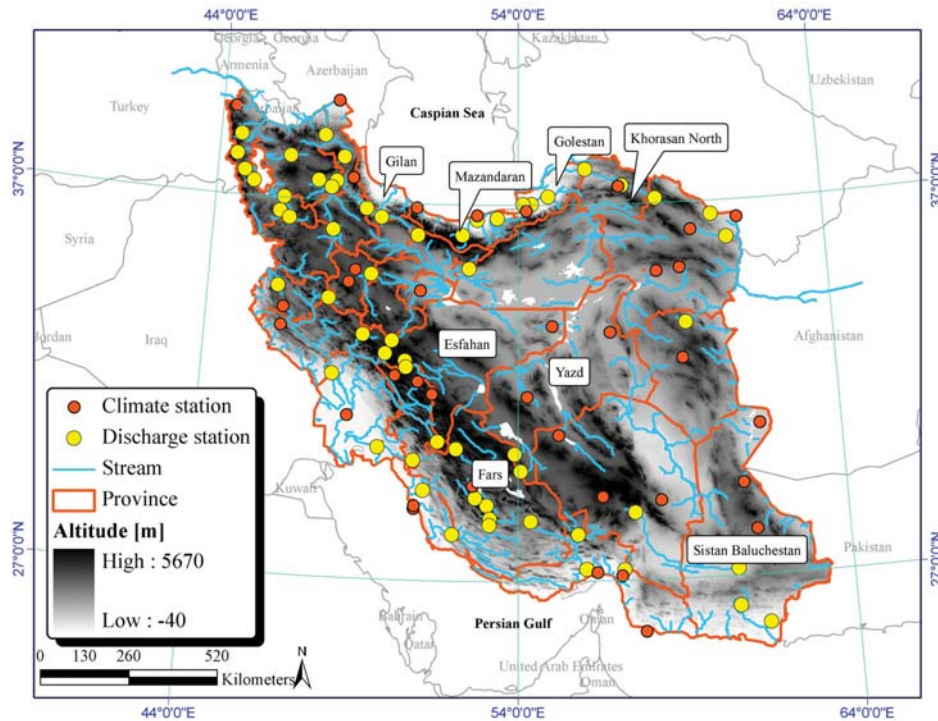


Figure 3.1 - An overview of Iran modeling details showing the elevation, streams, climate stations and discharge stations used in the model, as well as the provincial boundaries.

Iranian food and agriculture system and is grown on nearly 60 percent 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]. Owing to the traditional method of irrigation and water conveying systems, the irrigation water use efficiency varies between 15% and 36%. Therefore, a large fraction of diverted water is lost to evaporation and percolation.

In general, most of the country suffers from water resources scarcity. Figure 3.2 shows the per capita blue water resources distribution in the period of 1980-2002 based on the

population of the year 2005 [source *Faramarzi et al.*, 2009]. The spatial distribution of water resources availability 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 *Falkenmark et al.* [1989] and *Rijsberman* [2006]. Taking 1700 m³ per capita as the water scarcity threshold, about 46 million people living on about 59% of the country's area were subject to water scarcity.

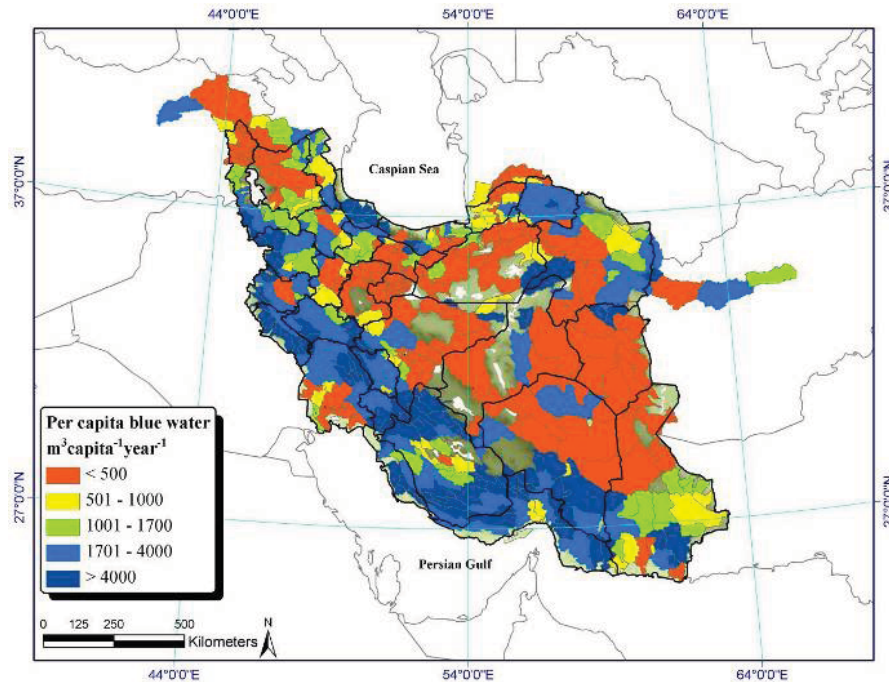


Figure 3.2 - Distribution of per capita blue water resources for the period of (1980-2002) based on the population of 2005. (Source: *Faramarzi et al.*, 2009).

3.2.2 The hydrologic simulator (SWAT)

SWAT is a computationally efficient simulator of hydrology and water quality at various scales. SWAT was developed to assess the impacts of landuse changes on water supplies and erosion in large-scale catchments. The model includes procedures to describe how CO₂ concentration, precipitation, temperature and humidity affect plant growth, evapotranspiration, snow and runoff generation, among other variables, and therefore is also used to investigate climate change impacts [*Eckhardt and Ulbrich*, 2003; *Fontaine et al.*, 2001; *Stonefelt et al.*, 2000].

The program has been used in many large-scale international applications [e.g., *Gosain et al.*, 2006; *Schuol et al.*, 2008a,b]. The model was developed to quantify the

impact of land management practices on water, sediment, and crop yield in large complex watersheds with varying soils, landuses, 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 (ver. 9.1) environment is used for project development.

Spatial parameterization of the SWAT model is performed by dividing a watershed into sub-basins based on topography, soil, landuse, and slope. The resulting units, referred to as hydrologic response units (HRUs), are used as the basis of water balance calculation. Water, sediment, and nutrient transformations and losses are determined for each HRU, aggregated at the sub-basin level, and then routed to the associated reach and catchment 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 modeling. 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 SCS curve number equation using the daily precipitation data based on soil hydrologic group, landuse and land-cover characteristics, and antecedent soil moisture.

In this study, potential evapotranspiration (PET) was simulated using Hargreaves method [Hargreaves and Samani, 1985]. Actual evapotranspiration (AET) was determined 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, which is a simplified version of the EPIC crop model [Williams *et al.*, 1984]. 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 used as dry economic yield to calculate crop yield. Plant growth can be inhibited by user-specified temperature, water, nitrogen, and phosphorus stress factors. A more detailed description of the model is given by Neitsch *et al.* [2002].

3.2.3 Future climate data and model scenarios

Global climate models, also known as general circulation models (GCM), numerically simulate changes in climate as a result of slow changes in some boundary conditions (such as the solar constant) or physical parameters (such as the greenhouse gas concentration). In this study, we used outputs of the Canadian Global Coupled Model (CGCM 3.1) version T63, which has a surface grid with a spatial resolution of roughly 2.8 degrees lat/long and 31 levels in the vertical. With this resolution 37 grid points fell inside Iran.

General circulation models (GCMs) contain significant uncertainties and *IPCC* [2007] recommends that the results of different models and scenarios should be considered in climate change studies. It has become standard practice to use several climate scenarios to characterize uncertainty in future climate [*Arnell et al.*, 2004]. In a hydrological impact study of climate change, the most important sources of uncertainty may arise from, in decreasing order, the emission scenarios [*Arnell et al.*, 2004], climate model parameterization (particularly for precipitation), downscaling [*Wilby and Harris*, 2006], and the hydrological model parameterization [*Wilby and Harris*, 2006; *Caballero et al.*, 2007]. In this work, we use three commonly used scenarios A1B, B1, and A2 from the widely used Canadian Global Coupled Model (CGCM 3.1). Results from the CGCM appear prominently in several Chapters in the IPCC report [*IPCC*, 2007, chapter 8-12] and form the basis of a variety of studies of climate change.

As GCMs are global models, they do not have suitable resolution for hydrologic modeling. Hence, they need to be downscaled to acceptable resolutions. Popular methods include change factor (CF) methodology whereby future changes in climate projected by GCMs are applied to a baseline climatology, and statistical downscaling methods where statistical transfer functions are used to estimate point-scale meteorological series [*Diaz-Nieto and Wilby*, 2005].

Within the CGCM we analyzed three commonly used scenarios: A1B, A2, and B1. The families of A1 scenario describe a future world of increasing globalization, and rapid but uniform global economic and technological growth with increasing materialistic and consumerist tendencies. The A1B scenario in this family depicts a world with a balanced use of fossil and non-fossil fuel as a main energy source. The A2 scenario describes a heterogeneous world with rapid but diverse regional economic and technological growth, and increasing materialistic and consumerist tendencies. The B1 scenario highlights an increasing global co-operation and convergence with more priority

given to environmental problems in the form of developing cleaner and more efficient technologies.

A key aspect of the climate change impact study is the spatial and temporal downscaling of the GCM results. In this study, the CGCM data were downscaled using the nearest observation station for the period of 1980-2002 in Iran. For rainfall, we used a simple ratio method where for each month we divided the average observed data by CGCM data and multiplied the daily CGCM data by this factor to obtain future daily rainfall data.

For the temperature we tested linear and non-linear models as used in the literature [Wilby et al., 1998], and chose a fourth degree regression model based on the calibration ($\approx 1990-2000$) and validation ($\approx 1982-1989$) results of stations in different regions. In general, the results of a first degree linear and a fourth degree non-linear model were more or less similar except for small and large temperature values, where the non-linear model performed systematically better, especially for the validation dataset. Hence, we opted for the nonlinear model.

3.2.4 Model inputs and model setup

Data required for this study were compiled from different sources. They include: Digital Elevation Model (DEM) data was extracted from the Global U.S. Geological Survey's (USGS) public domain geographic database HYDRO1k with a spatial resolution of 1 km (<http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html>). The land-cover map from the USGS Global Landuse Land-Cover Characterization (GLCC) database with a spatial resolution of 1 km, which distinguish 24 landuse and land-cover classes (<http://edcsns17.cr.usgs.gov/glcc/glcc.html>). The soil map was 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. Information about the digital stream network, 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 37 synoptic stations nearest to the CGCM's

grid data. 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 Ministry of Energy (MOE) of Iran for about 60 hydrometric stations for the period 1980-2002. Historical records on annual yield and area cultivated with irrigated wheat were obtained for the period 1980-2002 from the Agricultural Statistics and the Information Center of Ministry of Jahade-Agriculture and Statistical Center of Iran.

3.2.5 Calibration setup and analysis

In this study we recalibrated the model of *Faramarzi et al.* [2009] by removing the dams and irrigated agriculture, and subsequently, the stations that were affected by the dams. This was necessary as future landuse changes and dam operation could not be predicted with any accuracy. The spatial discretization resulted in 506 subbasins using dominant soil and landuse option. The hydrologic SWAT model was calibrated and validated at the subbasin level based on daily observed discharges at 60 stations across the country (Figure 1), and annual winter wheat yields at representative subbasins in each province. The combination of river discharge and crop yield in the objective function provides a more reliable estimate of both runoff and evapotranspiration and hence soil moisture and deep aquifer recharge. For details of the procedures for calibration, validation, sensitivity analysis, and uncertainty analysis we refer the readers to *Faramarzi et al.* [2009]. Some essential detail is provided below.

The SUFI-2 [*Abbaspour et al.*, 2007] algorithm in the SWAT-CUP program [*Abbaspour*, 2007] was used for parameter optimization. In this algorithm all uncertainties (parameter, conceptual model, input, etc.) are mapped onto the parameter ranges as the procedure tries to capture most of the measured data within the 95% prediction uncertainty. 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-*

factor $\rightarrow 1$) while having the narrowest band (*R-factor* $\rightarrow 0$). (More details on the SUFI-2 procedure can be found in *Abbaspour et al., 2007; Schuol et al., 2008a,b; and Yang et al. 2008*).

In order to compare the measured and simulated monthly discharges we used the following criterion modified from *Krause et al. [2005]*:

$$\Phi = \begin{cases} |b|R^2 & \text{for } 0 < |b| \leq 1 \\ |b|^{-1} R^2 & \text{for } |b| > 1 \end{cases}, \quad (2)$$

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:

$$g = \frac{1}{n} \sum_{i=1}^n \Phi_i, \quad (3)$$

where n is the number of stations. The function Φ varies between 0 and 1. Therefore the objective function, unlike, for example, Nash-Sutcliffe, is not dominated by one or a few badly simulated stations.

3.3 Results and discussion

3.3.1 Downscaling climate variables

The downscaled temperature data from CGCM agreed quite well with the recorded historical data. All 37 stations had R^2 values in the range of 0.92-1.00. The fit of the downscaled rainfall data was also relatively good as compared with the measured historical data. Figures 3.3a,b show the cumulative probability distribution of rainfall for the historic (1980-2002) and the CGCM data for a wet station in Gilan province near the Caspian Sea and a dry station in Esfahan province, central Iran. As shown in Figure 3.3a, in the wet region, smaller rainfalls (especially $\leq 2 \text{ mm day}^{-1}$) are slightly under-estimated by CGCM, while in the dry region (Fig. 3.3b) CGCM slightly over-estimates intermediate to large rainfall events. In Figures 3.3c and 3.3d the predicted long term average precipitations (mm day^{-1}) are compared with the historical data for different

scenarios in different time periods. As shown, major changes in the wet region occur in the fall season, while in the dry region, all seasons except summer experience some change. Figures 3.3e and 3.3f show average monthly changes in maximum temperature of wet and dry regions, respectively. Maximum temperature varies between 1-5 degrees in different scenarios with the highest occurring in July in the dry region for A2 scenario during the period 2070-2100.

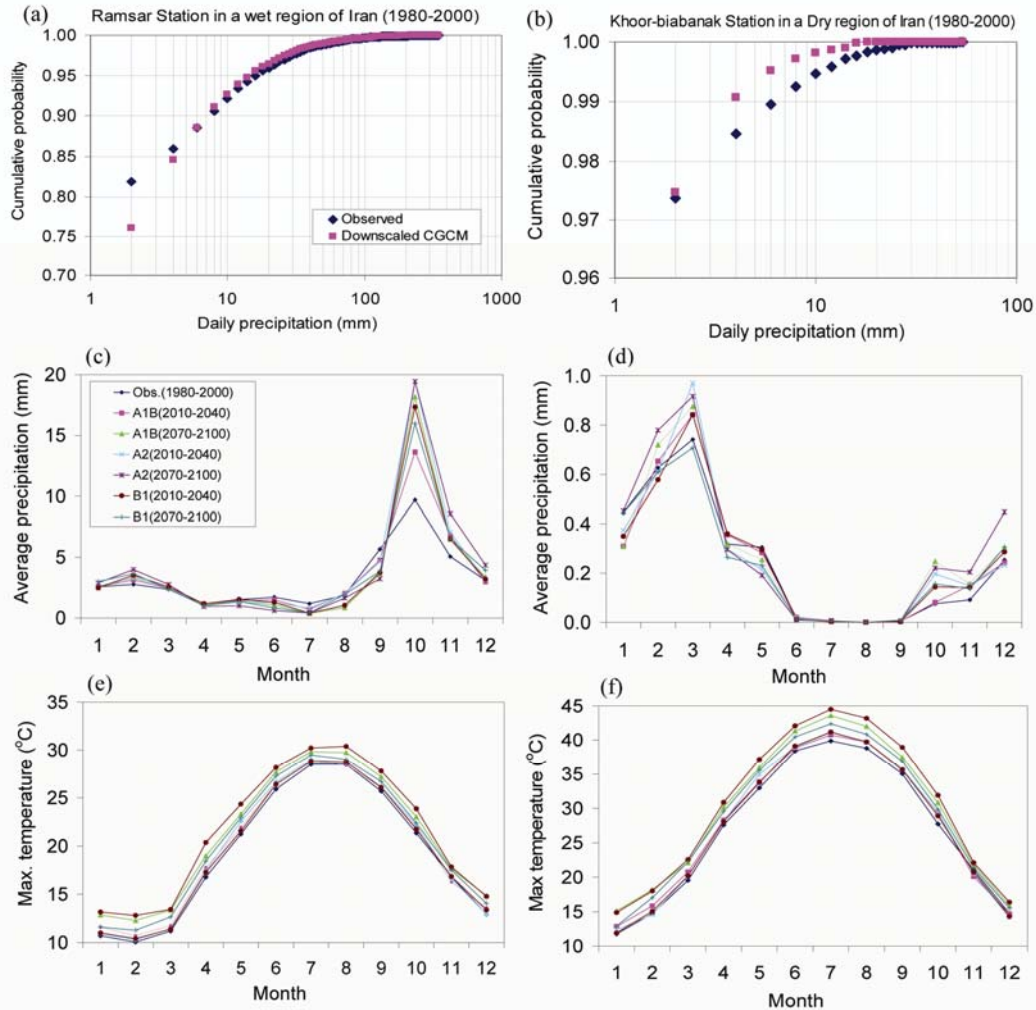


Figure 3.3 - Comparison of the downscaled precipitation (scenario A1B) in a wet (a) and dry (b) region of the country. Figures (c) and (d) compare average observed precipitation in each month for the same two stations with the three different scenarios and two time periods. Figures (e) and (f) compare maximum temperatures for the different scenarios.

3.3.2 Hydrological model calibration and uncertainty analysis

The hydrologic model of Iran was calibrated for the period of 1982-1992 and

validated for 1993-2002. Model performance was quite satisfactory across the country with the worst results being obtained in areas of intense water management. Figure 3.4 illustrates calibration results for two better-simulated stations from the wet and dry regions of the country. The shaded regions indicate the 95% prediction uncertainty (95PPU). In the wet region, the uncertainties are generally large as indicated by the *R-factor* (i.e., the average thickness of the 95PPU band divided by the standard deviation of the measured data. Based on our experience, a value close to 1 would be satisfactory), but there are a larger number of measured data bracketed by the 95PPU as indicated by the *P-factor* (i.e., percent data falling in the 95PPU band) signifying a more reliable model. In the dry region, model prediction uncertainty is smaller compared to the wet region, but still larger than desired. The large uncertainties are partly due to the lack of information in water management such as existence of reservoirs and regional water transfer [Faramarzi et al., 2009]. The R^2 and Nash-Sutcliffe (*NS*) coefficient, calculated between the best simulation (simulation with the largest objective function value) and the measured data, indicate quite satisfactory results for both regions. Similar results were obtained for model validation not shown here. For all stations, R^2 ranged between 0.1-0.8 for calibration and validation results.

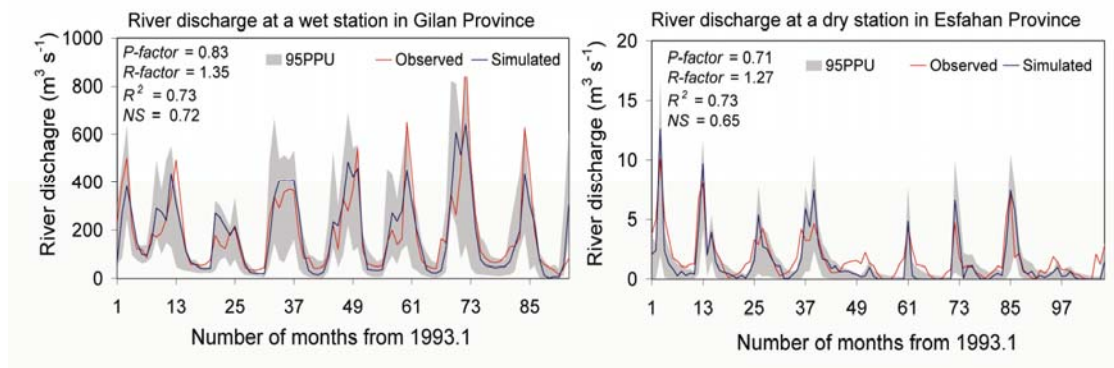


Figure 3.4 - Results of SWAT calibration for two selected hydrometric stations in the wet northern and dry southern regions of the country.

3.3.3 Impact of climate change on precipitation distribution

In Figure 3.5, the historic precipitation distribution (3.5a) and the anomaly maps (maps of percent deviation from historic data) are shown for the whole country for

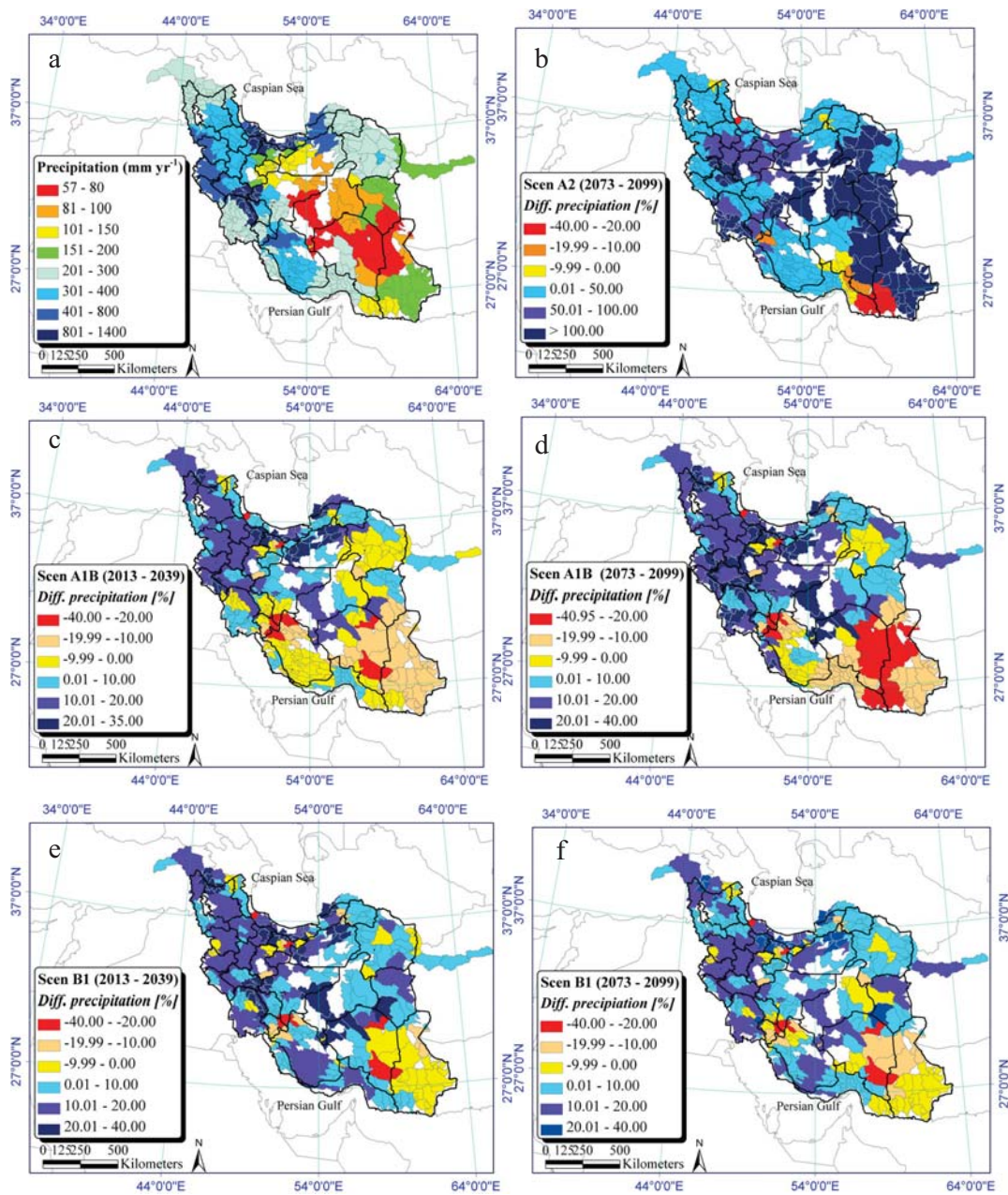


Figure 3.5 - The anomaly map of precipitation averages. Figure 3.5a shows the historic precipitation distribution. The percent differences are calculated based on the averages of data periods (2013-2039) and (2073-2099) from the average of (1980-2002).

different scenarios. The differences are calculated between the averages of (2013-2039) and (2073-2099) periods with those of the (1980-2002) period. While all scenarios show an increase in the precipitation in the northern and western parts of the country, there are major differences in the southern and eastern parts. The increases in the precipitation in the northern parts could be quite large, even as large as 40%. Prediction of rainfall in scenario A2 (3.5b) is exceptionally large for most of the country during 2073-2099.

Based on the CGCM, the south-eastern part of the country could experience up to a 40% decrease in precipitation in all scenarios. As precipitation is already small in this part of the country, the predicted decreases may have a significant effect on increasing droughts and hence crop production in this region as discussed later.

3.3.4 Impact of climate change on blue and green water

Currently, the definition of “blue water” is generally accepted as “the sum of the river discharge and the deep groundwater recharge”. This is in essence the water resources by the traditional hydrological and engineering definition. There exist slightly different definitions for the term “green water”. *Falkenmark and Rockstrom* [2006] differentiate between the green water “resource” and the green water “flow”. According to their definition, “green water resource is the moisture in the soil” which is a renewable resource and can potentially generate economic returns, as it is the source of the rainfed agriculture. The green water flow is composed of the actual evaporation (the non-productive part) and the actual transpiration (the productive part), commonly referred to together as the actual evapotranspiration. Using SWAT, we could distinguish the two different water resources components and study the effect of climate change on each component. Figure 3.6 shows the average values of blue water (mm year^{-1}) based on the historic data of 1980-2002 (3.6a) as well as the anomaly graphs for scenario B1 and A1B for periods 2013-2039 and 2073-2099 and scenario A2 for the period 2073-2099 as it is an extreme case. Generally, the blue water resources decrease from north to south and west to east. The near future simulations show an increase in blue water resources in the western half of the country while the central and eastern half experience a reduction in the already small water resources. In the far future, scenario A2 shows most of the country enjoying an increase in the blue water resources (3.6b). It should be noted, however, that an increase of >300% in the eastern regions of the country amounts to blue water resources of about 75 mm year^{-1} , which is still quite meagre in water resource sense but could have a substantial impact on the ecosystem of this desert region.

In the calculation of actual evapotranspiration, soil moisture, and groundwater recharge (maps not shown), we assumed that the land-cover in the future will stay the same as the period of 1980-2002. Hence, our results simply provide an indication of future changes rather than an actual scenario. As temperature increases, actual evapotranspiration (or green water flow) is also expected to increase if there is enough

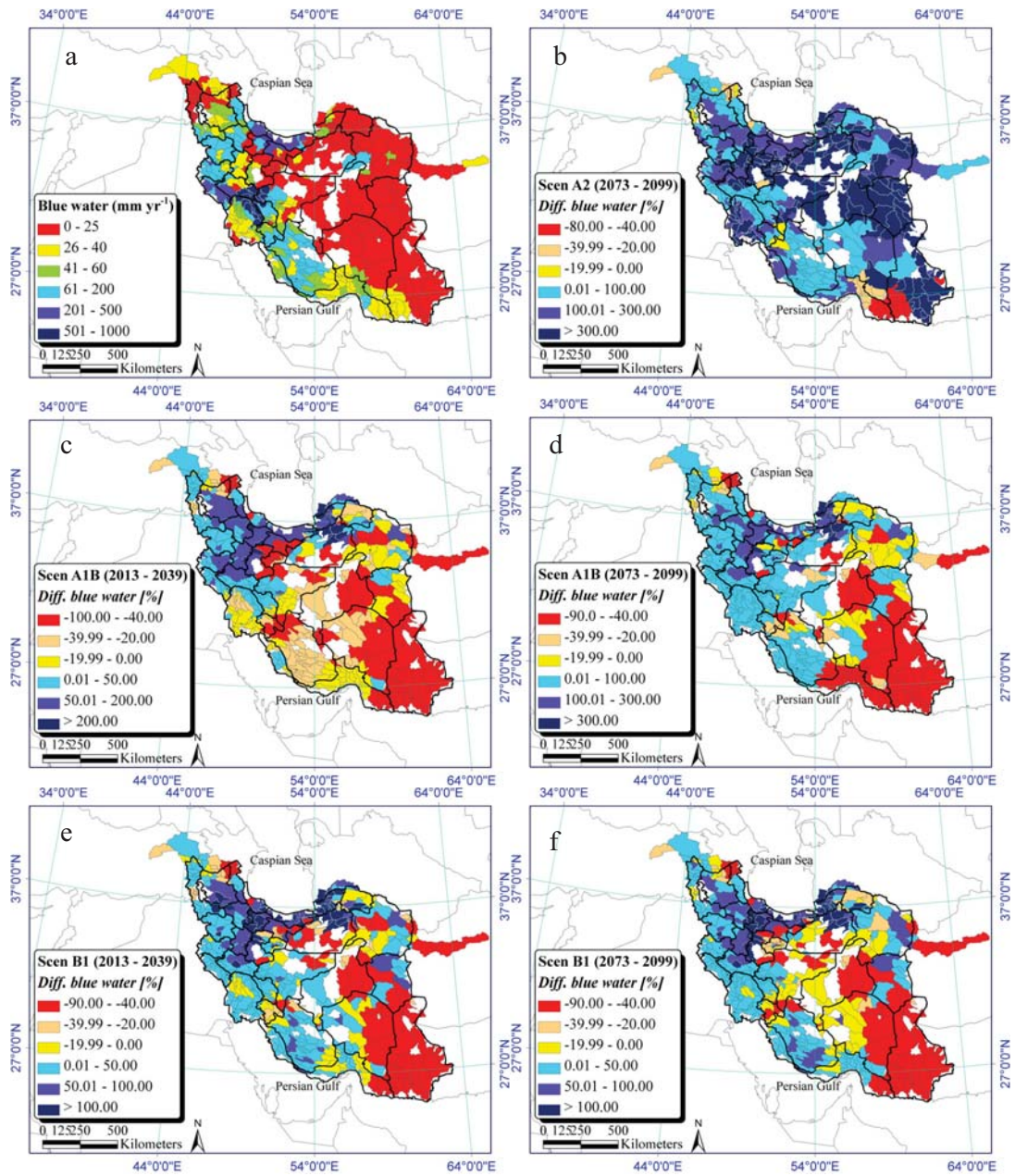


Figure 3.6 - Showing the effect of climate change on the blue water resources of the country. (a) Historic absolute values, (b) blue water anomaly based on scenario A2 for the period of (2073-2099), (c) blue water anomaly based on scenario A1B for the period of (2013-2039), and (d) results of scenario A1B for the period of (2073-2099), (e) blue water anomaly based on scenario B1 for the period of (2013-2039), and (f) results of scenario B1 for the period of (2073-2099).

water in the soil. Our calculations show AET slightly decreasing in large parts of the country in the north and west. This is because of the assumption that landuse and land-cover do not change; hence, as CO_2 increases, a smaller amount of water is needed to produce a target yield. In reality as CO_2 and temperature increase, there will be a denser

vegetation cover and a larger actual transpiration. This observation highlights that prediction of future landuse/land-cover is an important but difficult problem in climate change studies. All scenarios predict an increase in soil moisture for most regions of the country. We believe the future soil moisture is over-estimated for the same reason that evapotranspiration is under-estimated as discussed above.

Figure 3.7 shows the blue water resources and the green water flow aggregated at provincial level for four dry (right) and wet (left) provinces. These provinces were selected because they represent both climatic extremes and important agricultural production regions (see Figure 3.1 for the location of the provinces). In this figure, the hydrologic model uncertainties (size of the blue and yellow bars) are compared to the predictions of the three climate change scenarios (different columns). This figure was produced to highlight two points. First, the large differences in blue and green water flow between different scenarios more or less disappear when data is aggregated from subbasin to provincial level. This indicates the dependence of uncertainty analysis on the scale of the study (see also *Schuol et al.*, 2008b). Second, it appears that there is a greater uncertainty in the hydrological model results than the predictions of different climatic scenarios at the provincial scale. This is contrary to the remarks of *Caballero et al.*, [2007], which puts the major sources of uncertainty in decreasing order as emission scenarios, climate model parameterization, downscaling, and finally the hydrologic model parameterization. The order of uncertainty is perhaps dependent on the scale of the study with hydrologic model uncertainty becoming larger and the difference in emission scenario becoming smaller as the scale of study increases. It would perhaps be interesting to compare the outcome of different climate models for this part of the world. This analysis was not done in this study due to time constraints.

3.3.5 Impact of climate change on deep aquifer recharge

Calculation of aquifer recharge indicated that eastern half of the country will see decreases of up to 50-100% in groundwater recharge in regions that are already scarce in water resources. The north-western part of the country will see an increase in groundwater recharge due to an increase in rainfalls. All scenarios in the far future, as well as B1 scenario for the near future indicate an increase in the aquifer recharge in this region. As discussed above with respect to green water flow, recharge could be overestimated due to holding land cover constant in the model.

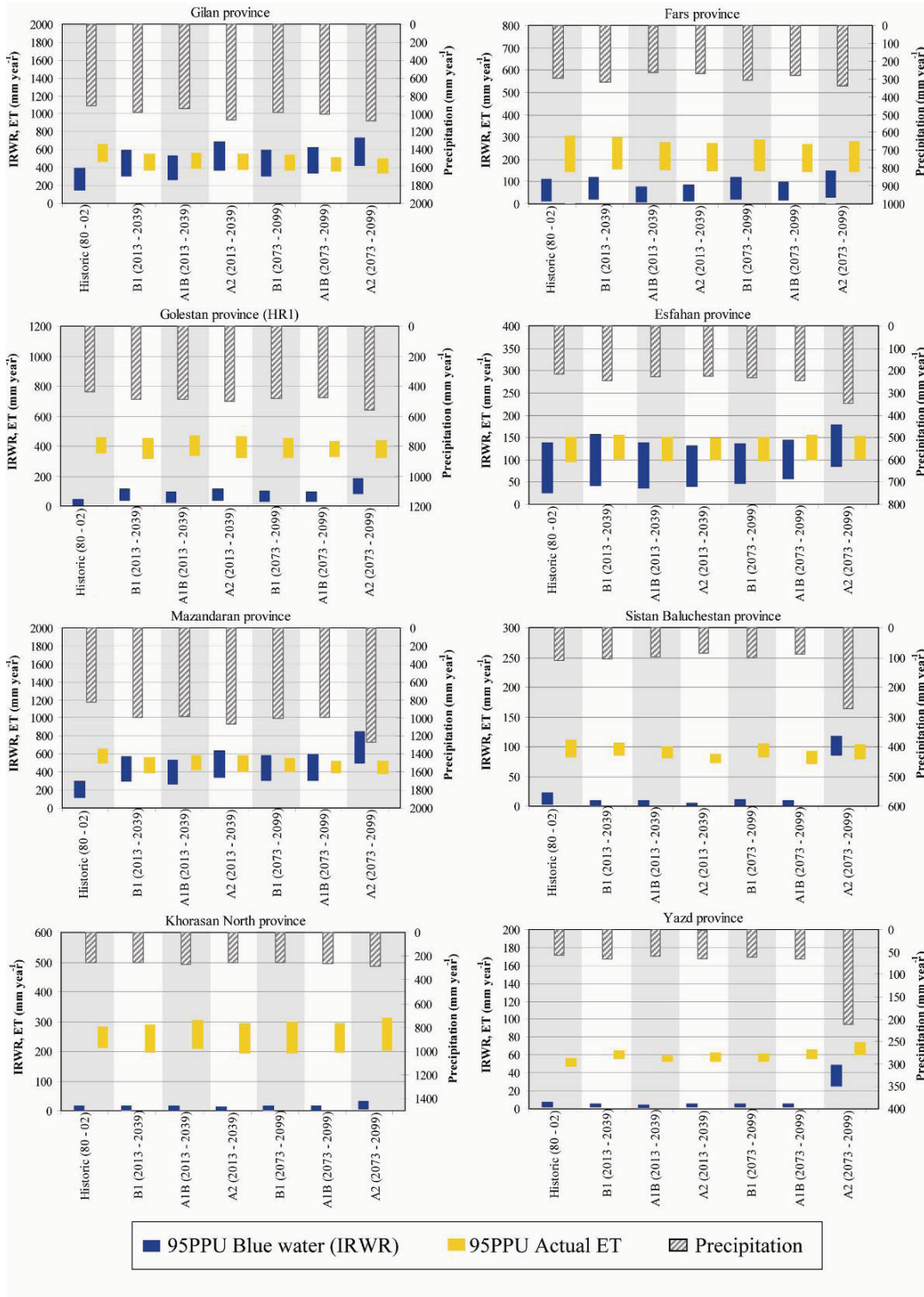


Figure 3.7. Blue water resources and green water flow aggregated at provincial level. The Figure compares the hydrologic model uncertainties (size of blue and yellow bars) to the differences in climate scenarios (different columns).

3.3.6 Impact of climate change on flooding and drought

Figure 3.8 shows the average distribution of the number of wet days (precipitation ≥ 2 mm day⁻¹) at four wet provinces in northern parts of the country for the historic (1980-2002) and the near future (2013-2039) scenarios. All four provinces show an increase in the number of days where rainfall ≥ 2 mm, except for the summer months. Khorasan (a province at the border of wet and dry region) shows a decrease in winter, but a moderate increase in summer rainfall, a shift which should have a positive effect on

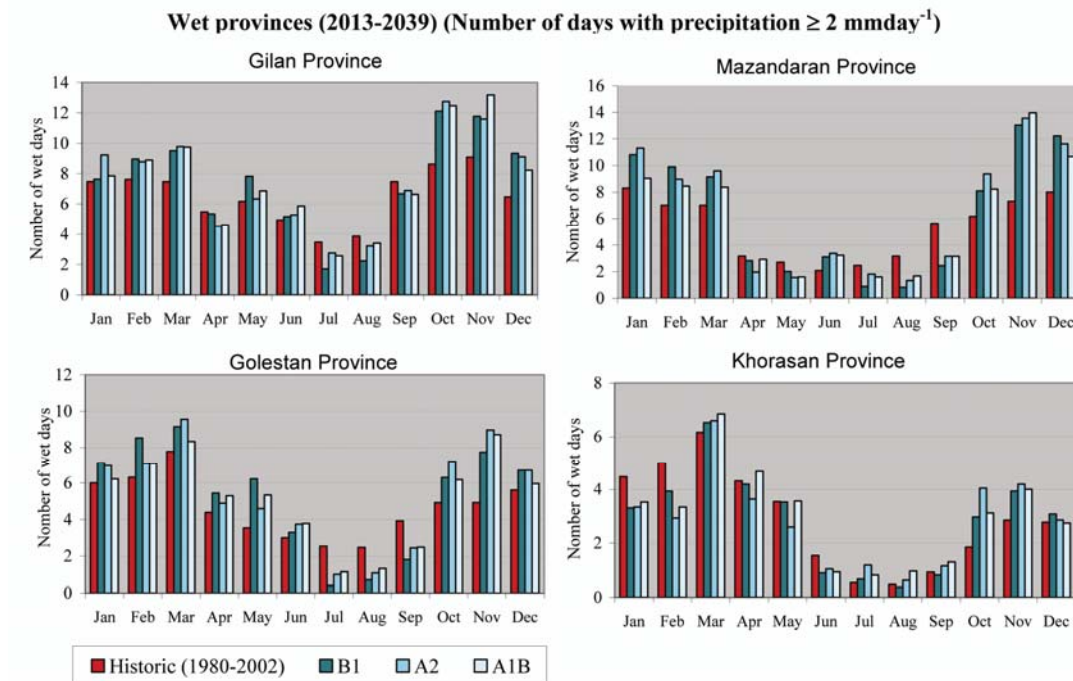


Figure 3.8 - Comparison of the number of wet days between historic and future climate conditions in wet regions of the country. In these graphs a wet day is defined as a day with precipitation ≥ 2 mm.

rainfed crop production in this province. Figure 3.9 and Figure 3.10 illustrate the number of days where the rainfall is ≥ 10 mm and ≥ 50 mm, respectively. Major increases are seen in the fall months indicating the possibility of larger and more frequent floods in the wet regions of the county. In Figure 3.10, there is a sharp increase in the number of days where precipitation is ≥ 50 mm in October and November.

Figure 3.11 shows the average number of wet days where rainfall is ≥ 2 mm day⁻¹ for four dry provinces in the central and southern part of the country. The results are different for each province from month to month and between different scenarios. In

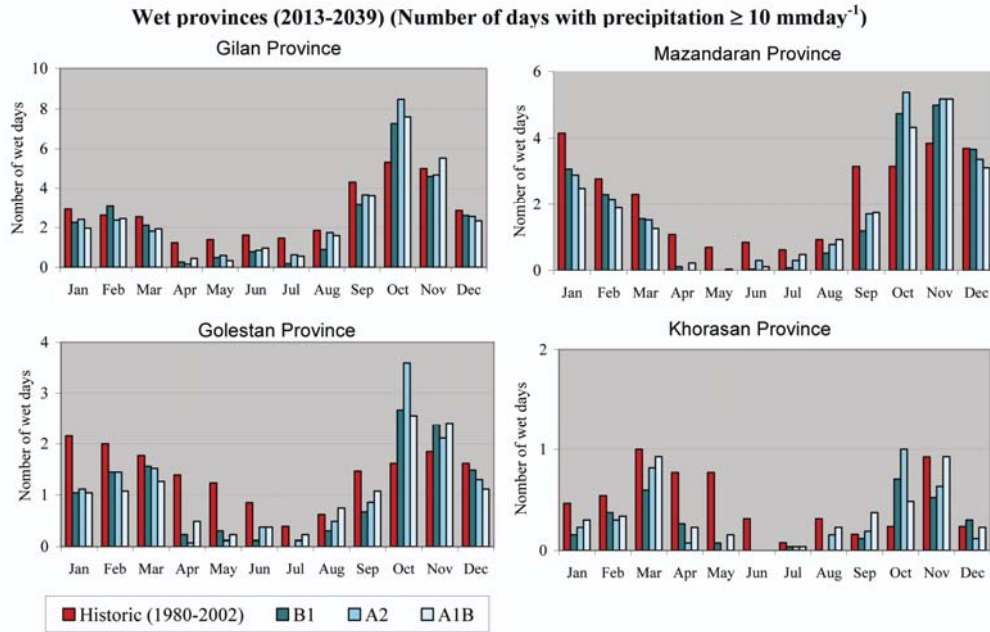


Figure 3.9 - Comparison of the number of wet days between historic and future climate conditions in wet regions of the country. In these graphs a wet day is defined as a day with precipitation ≥ 10 mm.

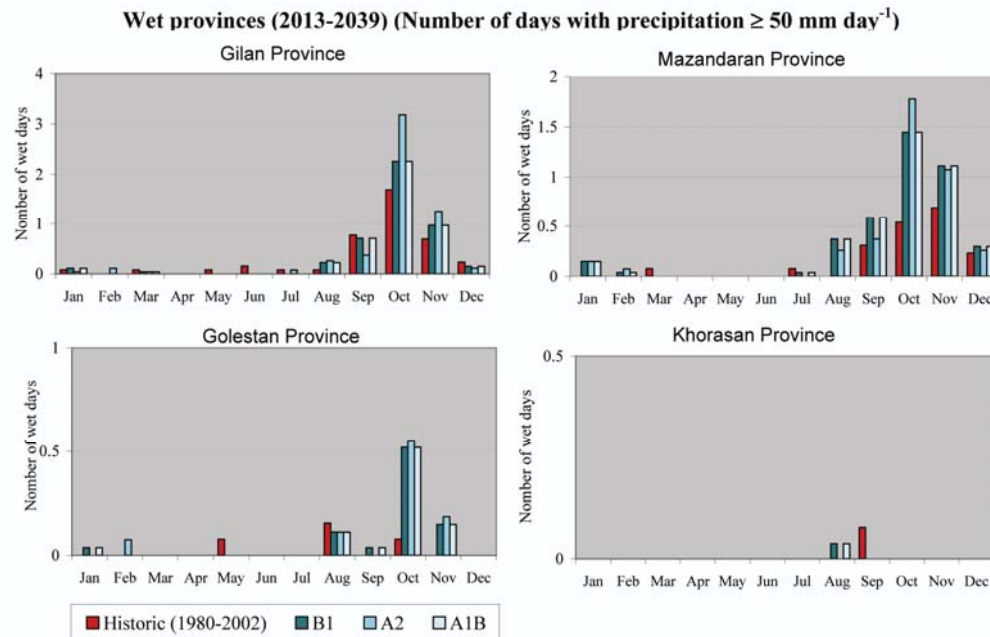


Figure 3.10 - Comparison of the number of wet days between historic and future climate conditions in wet regions of the country. In these graphs a wet day is defined as a day with precipitation ≥ 50 mm.

Esfahan and Yazd, there is a reduction in late spring rainfall with an increase in early fall

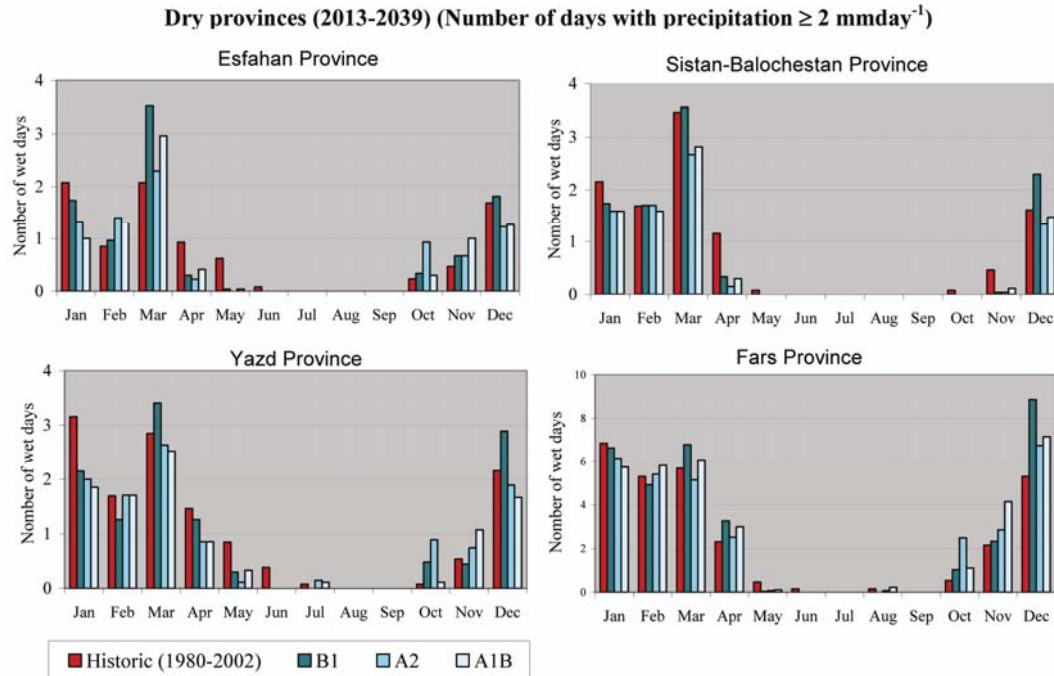


Figure 3.11 - Comparison of the number of wet days between historic and future climate conditions in dry regions of the country. In these graphs a wet day is defined as a day with precipitation $\geq 2 \text{ mm}$.

months. This shift will have important adverse consequences in crop production. In Sistan-Baluchestan both spring and fall experience fewer rainfall events, while Fars sees a general increase in the rainfall.

Figure 3.12 shows the number of days where rainfall is $\geq 10 \text{ mm}$ in the dry regions. The sharp reductions in the number of days with large rainfall events throughout the year will have significant consequences for water resources of these and similar provinces in dry regions of the country. Except for a few times in Fars, other dry provinces did not have any occurrences of rainfalls $\geq 50 \text{ mm day}^{-1}$.

In a further analysis, we plotted in Figure 3.13 the coefficient of variation (CV) of total annual precipitation for four dry and four wet provinces for the near and far future. The CV is an important indicator, as even small changes in it could indicate relatively large changes in the probability of occurrence of extreme events. In general, for the near future, the CVs of total precipitation for wet provinces (Gilan, Mazandaran, Golestan) are larger than the historic ones. This indicates a stronger year to year variation in total precipitation in these provinces. For example, for the province of Gilan, scenario A2 predicts total rainfall of larger than 4000 mm in some years and smaller than 650 mm in

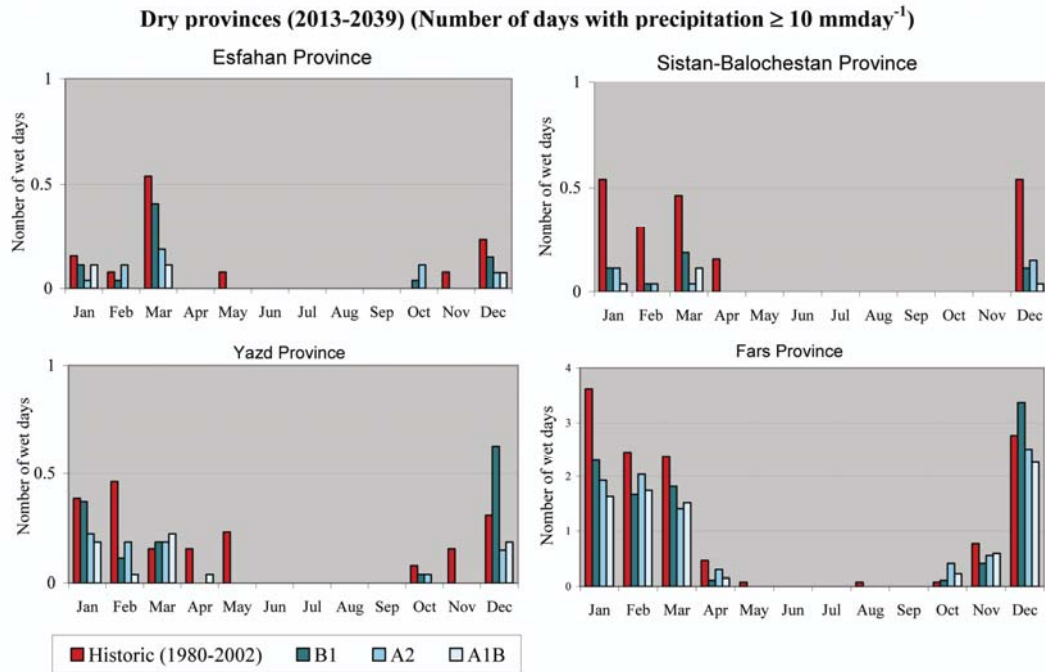


Figure 3.12 - Comparison of the number of wet days between historic and future climate conditions in dry regions of the country. In these graphs a wet day is defined as a day with precipitation ≥ 10 mm.

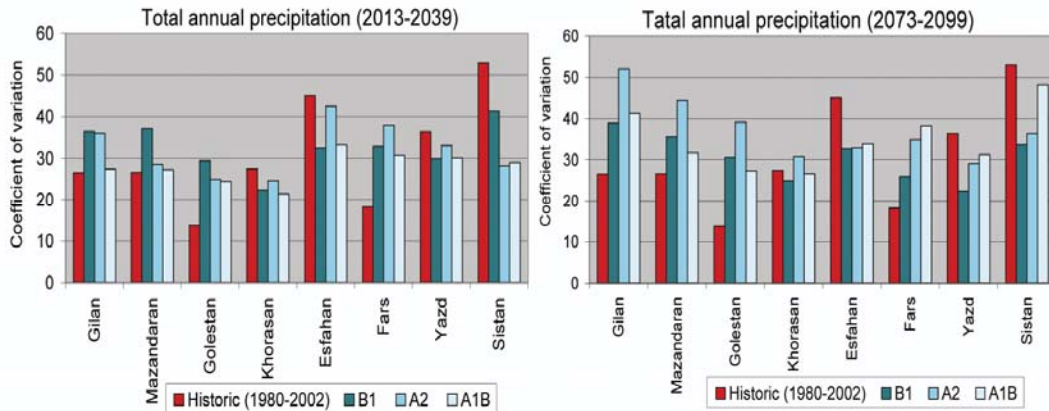


Figure 3.13 - Coefficient of variation of total annual precipitation for wet and dry provinces based on different climate scenarios for near and far future periods.

others. In dry provinces, except for Fars, the year to year variations in total precipitation seem to be smaller. The same trend could be seen for the far future, but with more pronounced differences with the historic CVs.

In Figure 3.14, we plotted the CV of the number of wet days per year for precipitations of ≥ 2 mm and ≥ 10 mm day⁻¹. Only Esfahan shows a substantially larger CV

for $\geq 2\text{mm day}^{-1}$ rainfalls, while other provinces show more or less similar or smaller for $\geq 10\text{ mm day}^{-1}$ rainfall, however, the CV is much larger for the dry provinces, indicating intermittent extreme events.

Finally, in Figure 3.15 we plotted the CVs of maximum temperature for a typical wet and a typical dry province. In general, in the wet provinces the daily variation of maximum temperature is the same or smaller in different months, while in dry provinces this is larger, indicating some extreme high temperatures. The same was true for minimum temperature (not shown). We have also studied the CV of the difference of maximum and minimum temperature. While this variation was slightly smaller in wet provinces, it was slightly larger in dry provinces. Further and more detailed research at a regional scale is needed to quantify the exact effect of these changes on the crop production and biodiversity of the region. Below we highlight some general implications

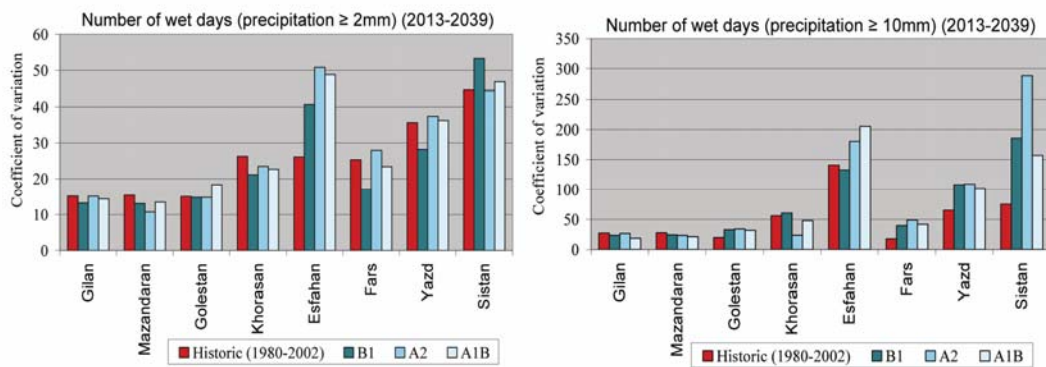


Figure 3.14 - Coefficient of variation of the number of wet days. The left figure shows precipitation $\geq 2\text{ mm day}^{-1}$, and the right Figure shows precipitation $\geq 10\text{ mm day}^{-1}$ for wet and dry provinces. variations.

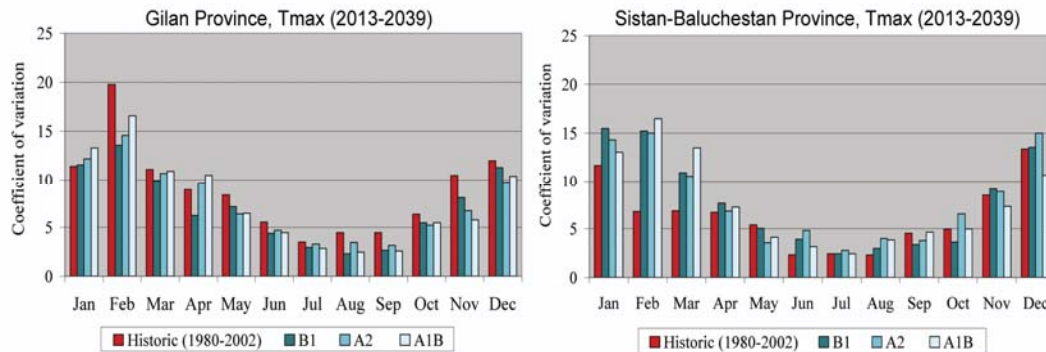


Figure 3.15 - Coefficient of variation for maximum temperature in different months for a wet and a dry province.

of the changes in the future climate.

3.3.7 Implications of the climate change impacts

Flooding in the northern and western part of the country is historically a common occurrence. Heavy torrential rains during August 2001 triggered devastating floods that damaged rice, cotton, and wheat producing areas of Golestan and Khorasan provinces [National Report of I.R. of Iran on Disaster Reduction, 2005]. These floods damaged thousands of hectares of farmland in Iran, claimed hundreds of lives, and washed away roads and houses, causing millions of dollars in damage. Similar floods were reported again in January 2004 along the western side of the Zagros Mountains in the western part of the country. A further increase in precipitation could increase the frequency and intensity of floods in the wet regions of the country. It is evident from the changes in precipitation (Figure 3.5) and blue water resources (Figure 3.6) as well as the increases in the number of large rainfall events (Figures 3.9 and 3.10) that the northern and western regions of the country will experience a larger and more intense flooding events.

Drought is estimated by the United Nation to have cost Iran 3.5 billion dollars in 2000, and mid-year estimates for 2001 were already at 2.5 billion (*Tehran Times*, July 2001, p. 4). In July 2001 fifty villages in Kerman Province in central Iran were evacuated for lack of water [Foltz, 2002]. Over one million head of live stock perished throughout the country in 2000 due to drought, and three million tons of wheat and barley were lost. A further decrease in precipitation could increase the frequency and intensity of droughts in the dry regions of the country. It is again evident from our analysis that the southern and eastern regions of the country will experience lesser rainfalls (Figure 3.5), smaller aquifer recharges, and longer periods without a major rainfall event (Figures 3.11, 3.12). Hence, they are susceptible to more severe drought conditions.

In many parts of Iran, the water supply solely depends on groundwater. During the last two decades an over-exploitation of this resource has caused a drawdown in water table in most of the 600 aquifers in Iran [Motagh *et al.*, 2008]. Groundwater quality on the other hand, has also been degrading continuously because of agricultural and industrial activities in most regions of the country [Tizro and Voudouris, 2008]. Our analysis shows a decrease in groundwater recharge in water scarce regions of south and east. As much of the irrigated wheat is grown in the southern and eastern regions, climate change will have a significant negative impact on the wheat production of the country as

groundwater recharge decreases.

Our analysis of crop yield, however, shows small but statistically insignificant increases in winter wheat yield for most provinces. The small increase is probably due to the larger soil moisture, temperature, and more importantly air CO₂ concentration. According to the Global Geographic Distribution Map of Major Crops [Leff *et al.*, 2004], which has a spatial resolution of 30 arc-minutes and our findings, 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, 50% of irrigated and rain-fed wheat is produced in water scarce regions. Although the impact on rainfed yield appears to be small as the result of changes in temperature and rainfall patterns, the impact on irrigated yield is expected to decrease yield substantially in the dry regions of the country because of the decrease in blue water resources (Figure 3.6), which is river discharge plus groundwater recharge.

Although we did not simulate water quality, increased precipitation in the northern and western part of the county may increase the risk of water source contamination from sewage overflows, and runoff from agricultural land and urban areas as well as increased sediment and non-point source pollutant loadings to watercourses. As our hydrological model was not calibrated for sediment yield, we could not quantify the impact of climate change on soil erosion. As soil erosion is already large in the country [Rostamian *et al.*, 2008], areas with larger amounts of rainfall are expected to have even larger soil erosion affecting crop yield, sedimentation problems in the reservoir, and river water quality. On the other hand, prolonged droughts may result in smaller river discharges and a decline in reservoir levels causing water quality deterioration as nutrients and contaminants become more concentrated in reduced volumes with longer water residence times. Warmer water temperatures may have further direct impacts on water quality, such as increasing algae growth and reducing dissolved oxygen concentrations. Cold-water species, such as trout, are particularly susceptible to warm water temperatures, and increasingly frequent warm water conditions could bring new challenges to the way managed river systems are controlled. In addition, evaporative water losses could increase the salinity of soils in irrigated areas and surface waters, especially in lakes and reservoirs with long residence times. Contaminants tend to accumulate on land surfaces during prolonged droughts. Pulses of contaminated runoff can occur when precipitation returns. Water quality impacts are, therefore, likely to be rather complex and will vary with the physical, geographical and biological details of each water supply.

As the SWAT hydrologic model was run for 506 subbasins across the country and daily time steps, a substantial amount of information is generated for each subbasin. Of these, we provided an overview of the impact of climate change on various hydrologic components for the whole country. These analyses could be very useful in strategic planning of water resources management and crop production for the future years. As different subbasins are affected differently, a number of management options could be considered in order to alleviate the climate change impact on the country as a whole. In terms of food security, these could include changes in the structure of crop production (landuse change) and intra-country virtual water trade between subbasins (or provinces) utilizing local comparative advantages. These are the subjects of our continuing studies.

References

- Abbaspour, K. C. (2007) User Manual for SWAT-CUP, SWAT Calibration and Uncertainty Analysis Programs, 93 pp., Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.
- http://www.eawag.ch/organisation/abteilungen/siam/software/swat/index_EN
- Abbaspour, K.C., J. Yang, I. Maximov, R. Siber, K. Bogner, J. Mieleitner, J. Zobrist, and R. Srinivasan (2007), Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J. Hydrol.*, 333, 413-430.
- Ardakanian, R. (2005), Overview of water management in Iran, in *Water conservation, reuse, and recycling*, Proceeding of an Iranian American workshop, pp. 18-33, The National Academies Press: Washington, D.C.
- Arnell, N. W., M. J. L. Livermore, S. Kovats, P. E. Levy, R. Nicholls, M. L. Parry, and S. R. Gaffin (2004), Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines, *Global Env. Change*, 14, 3-20.
- Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams (1998), Large area hydrologic modeling and assessment - Part 1: Model development, *J. Am. Water Resour. Assoc.*, 34(1), 73-89.
- Caballero, Y., S. Voirin-Morel, F. Habets, J. Noilhan, P. LeMoigne, A. Lehenaff, and A. Boone (2007), Hydrological sensitivity of the Adour-Garonne river basin to climate change, *Water Resour. Res.*, 43, W07448, doi:10.1029/2005WR004192.
- Calanca, P., A. Roesch, K. Jasper, M. Wild (2006), Global warming and the summertime

- evapotranspiration regime of the Alpine region, *Climatic Change*, 79(1-2), 65-78.
- Cuo, L., D. P. Lettenmaier, M. Alberti, and J. E. Richey (2009), Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin, *Hydrological Processes*, 23(6), 907-933.
- Diaz-Nieto, J., and R. L. Wilby (2005), A comparison of statistical downscaling and climate change factor methods: Impacts on low flows in the river Thames, United Kingdom, *Climatic Change*, 69, 245-268.
- Falkenmark M, and J. Rockstrom (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. *J. Water Res. Pl-ASCE*, 132(3), 129-132.
- Falkenmark M, J. Lundquist, and C. Widstrand (1989), Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. *Nat. Resour. Forum*, 13(4), 258-267.
- Faramarzi, M., K.C. Abbaspour, R. Schulin, and H. Yang (2009), Modelling blue and green water resources availability in Iran, *Hydrol. Proc.* 23(3), 486-501.
- Foltz R. C. (2002), Iran's water crisis: Cultural, political, and ethical dimensions. *J. of Agric. and Env. Ethics*, 15, 357-380.
- Fontaine, T. A., J. F. Klassen, T. S. Cruickshank, and R. H. Hotchkiss (2001), Hydrological response to climate change in the Black Hills of South Dakota, USA, *Hydrol. Sci. J.*, 46, 27-40.
- Food and Agriculture Organization, FAO (1995), *The digital soil map of the world and derived soil properties*. CD-ROM, Version 3.5, Rome.
- Food and Agriculture Organization, FAO (2005), Statistical database, Food and Agriculture Organization of the United Nations, Available at the World Wide Web: <http://faostat.fao.org/>.
- Fu, G., S. P. Charles, N. R. Viney, S. L. Chen, and J. Q. Wu (2007), Impacts of climate variability on stream-flow in Yellow River, *Hydrol. Proc.*, 21(25), 3431-3439.
- Gosain, A. K., S. Rao, and D. Basuray (2006), Climate change impact assessment on hydrology of Indian river basins, *Curr. Sci.*, 90, 346-353.
- Hargreaves, G., and Z. A. Samani (1985), Reference crop evapotranspiration from temperature, *Applied Engr. Agr.*, 1, 96-99.
- IPCC (2007), Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Parry, Martin L., Canziani, Osvaldo

- F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 1000 pp.
- Jyrkama, M. I., and J. F. Sykes (2007), The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario), *J. Hydrol.*, 338(3-4), 237-250.
- Keshavarz, A., S. Ashrafi, N. Hydari, M. Pouran, and E. Farzaneh (2005), Water allocation and pricing in agriculture of Iran, in *Water conservation, reuse, and recycling*, Proceeding of an Iranian American workshop, pp. 153-172, The National Academies Press: Washington, D.C.
- Krause P., D. P. Boyle, and F. Bäse (2005), Comparison of different efficiency criteria for hydrological model assessment, *Adv. Geosci.*, 5, 89-97.
- Leff B., N. Ramankutty, J. A. Foley (2004), Geographic distribution of major crops across the world, *Global Biogeochemical Cycles* 18, GB1009. DOI: 10.1029/2003GB002108.
- Motagh, M., T. R. Walter, M. A. Sharifi, E. Fielding, and A. J. Schenk (2008), Land subsidence in Iran caused by widespread water reservoir overexploitation, *Geophys. Res. Lett.*, 35, L16403.
- Neitsch, S. L., J. G. Arnold, J. R. Kiniry, J. R. Williams, and K.W. King (2002), *Soil and Water Assessment Tool*, 458 pp., Theoretical documentation: Version 2000, TWRI TR-191, College Station, Texas: Texas Water Resources Institute.
- Nunes, J. P., J. Seixas, J. J. Keizer, and A.J.D. Ferreira (2009), Sensitivity of runoff and soil erosion to climate change in two Mediterranean watersheds. Part I: model parameterization and evaluation, *Hydrol. Proc.*, 23 (8), 1202-1211.
- Olivera F., M. Valenzuela, R. Srinivasan, J. Choi, H. D. Cho, S. Koka, and A. Agrawal (2006), ArcGIS-SWAT: A geodata model and GIS interface for SWAT. *J. Am. Water Resour. As.*, 42(2), 295-309.
- Rijsberman F. R. (2006), Water scarcity: Fact or fiction? *Agricultural Water Manage.*, 80, 5-22. DOI:10.1016/j.agwat.2005.07.001.
- Ritchie J. T. (1972), A model for predicting evaporation from a row crop with incomplete cover, *Water Resour. Res.*, 8: 1204-1213.
- Rostamian, R., A. Jaleh, M. Afyuni, S. F. Mousavi, M. Heidarpour, A. Jalalian, and K. C. Abbaspour (2008), Application of SWAT Model for Estimating Runoff and Sediment in a Mountainous Watershed in Central Iran, *Hydrol. Sci. J.*, 53, 977-988.

- Schuol, J., K. C. Abbaspour, R. Sarinivasan, and H. Yang (2008a), Estimation of freshwater availability in the West African Sub-continent using the SWAT hydrologic model, *J. Hydrol.*, 35, 30-49.
- Schuol, J., K. C. Abbaspour, R. Srinivasan, and H. Yang (2008b), Modelling Blue and Green Water Availability in Africa at monthly intervals and subbasin level, *Water Resour. Res.*, 44, W07406, doi:10.1029/2007WR006609.
- Scibek, J., and D. M. Allen (2006), modeled impacts of predicted climate change on recharge and groundwater levels, *Water Resour. Res.*, 42(11), W11405, doi:10.1029/2005WR004742.
- Serrat-Capdevila, A., J. B. Valdes, J. G. Perez, K. Baird, L. J. Mata, and T. Madock III (2007), Modeling climate change impacts - and uncertainty - on the hydrology of a riparian system: The San Pedro Basin (Arizona/Sonora), *J. Hydrol.*, 347(1-2), 48-66.
- Stonefelt, M. D., T. A. Fontaine, and R. H. Hotchkiss (2000), Impacts of climate change on water yield in the Upper Wind River Basin. *J. Am. Water Resour. Assoc.*, 36, 321-336.
- Thomas, D.S.G., C. Twyman, and H. Osbahr (2007), Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa, *Climatic Change*, 83(3), 301-322.
- Tizro, A. T., and K. S. Voudouris (2008), Groundwater quality in semi-arid region of the Chahardouly Basin, West Iran, *Hydrol. Process.*, 22(16), 3066-3078.
- Wilby, R. L., H. Hassan, K. Hanaki (1998), Statistical downscaling of hydro-meteorological variables using general circulation model output. *J. Hydrol.*, 205(1-2), 1-19.
- Wilby, R. L., and I. Harris (2006), A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK, *Water Resour. Res.*, 42, W02419, doi:10.1029/2005WR004065.
- Williams, J. R., C. A. Jones, and P. T. Dyke (1984), A modeling approach to determining the relationship between erosion and soil productivity, *Trans ASAE*, 27(1), 129-144.
- Xiong, K.G., J. Yang, S.Q. Wan, G.L. Feng, and J.G. Hu, (2009), Monte Carlo simulation of the record-breaking high temperature events of climate change, *Acta Physica Sinica*, 58(4), 2843-2852.
- Yang, H., P. Reichert, K. C. Abbaspour, and A. J. B. Zehnder (2003), A Water Resources

Threshold and Its Implications for Food Security. *Env. Sc. & Tech.*, 37(14), 3048-3054.

Yang, J., P. Reichert, K. C. Abbaspour, and H. Yang (2008), Comparing uncertainty analysis techniques for a SWAT application to Chaohe Basin in China, *J. Hydrol.*, 358, 1-23.

AGRICULTURAL WATER MANAGEMENT 97: 1861-1875 2010**4 MODELLING WHEAT YIELD AND CROP WATER PRODUCTIVITY IN IRAN: IMPLICATIONS OF AGRICULTURAL WATER MANAGEMENT FOR WHEAT PRODUCTION**

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Abstract

In most 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 plant-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 the 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 crop 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 more sustainable agricultural strategy.

Keywords: Uncertainty analysis; SWAT; SUFI-2; Iran; Wheat; Yield calibration

4.1 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, hydro-geologic, and socio-economic conditions in the country. Although 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 percent 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 developed to describe 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 only address crop yield and not crop water consumption. Some examples of 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, 2007), InfoCrop (Aggarwal et al., 2006), and WaterGAP (Alcamo et al., 2003). Process-based models are often either strong in crop growth simulation or in hydrology but not in both fields. 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 the water resources availability of that area. Therefore, one cannot assess directly the combined impact of regional water resources availability, landuse change, and climate change on crop production. Furthermore, process-based models are often applied without adequate calibrated and validation and 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 study (Faramarzi et al., 2009), we developed a hydrological model of Iran using the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). In the present study, we extended the hydrologic model to include crop yield using the crop growth module provided by SWAT. Our main objective was to model the basin-wide spatial and temporal variation of wheat yields and consumptive water use in Iran with uncertainty analysis at sub-basin scale, and to use the calibrated model to determine *CWP* for those areas. A secondary objective was to compare wheat productivity of irrigated and rainfed wheat alternatives. As statistical data was only available at the provincial level, calibration and validation could only be performed at that level. With the analysis of the current status of water demand and water supply in Iranian agriculture we hope to provide for improvement Iran's agricultural water management in the future. For this purpose, we in particular discuss the feasibility of promoting interregional virtual water trade and the potential use of our results for analyzing policy options.

4.2 Materials and methods

4.2.1 Description of the study area

Geographically, Iran is located between 25 to 40 degrees north latitude and 44 to 63 degrees east longitude with total area of about 1.648 million km². Although climatic conditions are mostly arid and semi-arid, the country shows a wide spectrum of climatic,

physiographic, edaphic, and hydrological conditions. The country-wide average precipitation is about 250 mm year⁻¹. The northern part and the high altitude areas in the west of the country receive about 1600-2000 mm year⁻¹ (NCCO, 2003), while the central and eastern parts receive less than 120 mm year⁻¹. Iran's per capita freshwater availability was estimated at around 2000 m³ capita⁻¹ year⁻¹ in the year 2000 and expected to fall below 1500 m³ capita⁻¹ year⁻¹ by 2030 due to population growth (Yang et. al., 2003). Winter temperatures can drop below -20 °C at high altitudes, and summer temperatures of more than 50 °C have been recorded in some areas (NCCO, 2003).

According to the information available from the Global USGS landuse map, the Global Map of Irrigation Areas Version 4.0.1 (Siebert et al., 2007), the USDA (USDA, 2003) and other sources such as Statistical Center of Iran (SCI), roughly 12% of country's land surface or 18.5 million hectares distributed across 30 provinces, are devoted to field crop production and horticulture (Alizadeh and Keshavarz, 2005). About 9 million hectares of this land are irrigated, using traditional as well as modern techniques, around 6.5 million hectares are rainfed, and the rest is fallow. Most of the arable land is devoted to wheat cultivation. Wheat is grown on nearly 60 percent of the country's total area under cultivation. The average yield for irrigated wheat in Iran is approximately 3.0 tons ha⁻¹, compared to 0.95 tons ha⁻¹ for rainfed wheat (FAO, 2002). The variation of crop water productivity is reported to be 0.14 to 1.0 kg m⁻³ for wheat across the country (Banaei et al., 2005). Figure 4.1 shows how the country's yield, crop area, and production developed over the past two decades. The large dip in the production in 1999 was due to a severe drought during which many major rivers such as the Zayandeh Rud dried up. Both irrigated and rainfed farming systems are practiced in different parts of the country. The areas devoted to these systems vary considerably from region to region depending on agro-climatic conditions. Rainfed agriculture is dominant in the western and northwestern Iran, as well as the sloping lands along the Caspian coast. Also in other parts of the country, dryland farming is practiced in hilly areas, but yields are rather low. In the central plateau, as well as the southern plains and areas where rainfall is extremely small and evaporation is large, crop production is dominated by irrigated agriculture. In some central Iranian provinces, the annual rainfall is about 120 mm, while the annual evapotranspiration can exceed 1000 mm on irrigated lands (Akbari et. al, 2007; Faramarzi et. al., 2009). 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

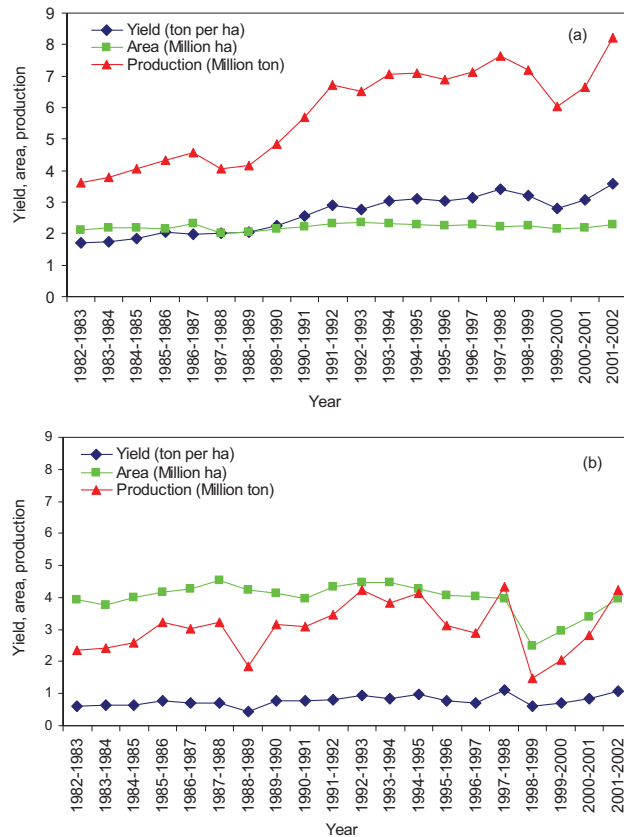


Figure 4.1 - Historical yield, area, and production for (a) irrigated wheat, and (b) rainfed wheat. The large dip in the production reflects the severe drought event during 1999-2001.

most central, northeastern and southern areas of the country. Since 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, almost no agriculture is practiced because of the harsh climatic conditions, in particular the lack of water. This study only considered the subbasins where crop production is practiced (Figure 4.2).

4.2.2 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

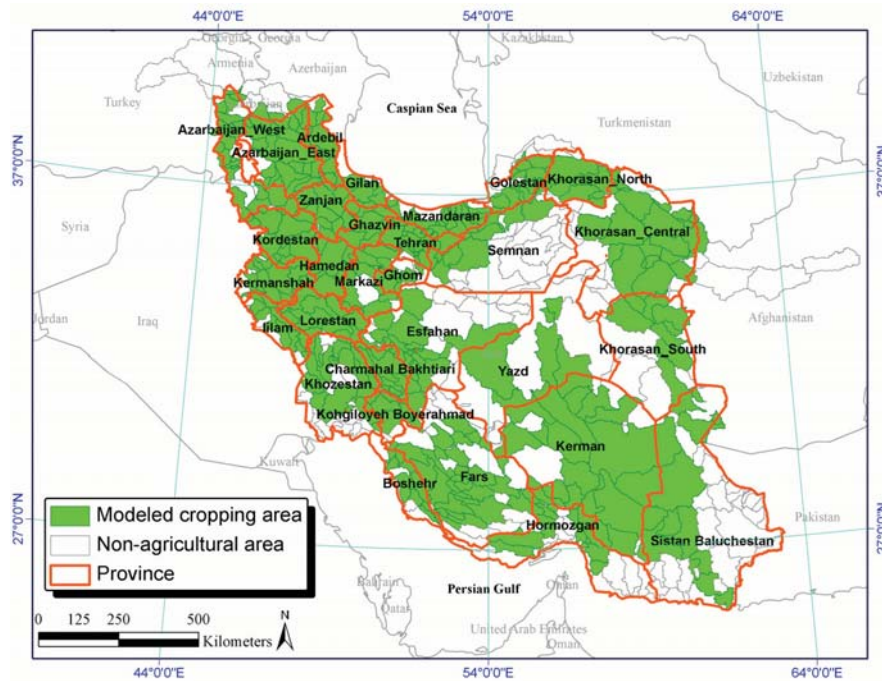


Figure 4.2 - Study area and the modeled sub-basins where wheat is grown.

scales and environmental conditions from small catchments to continental level (Gassman et al., 2007). It simulates plant growth processes as well as hydrological processes. In this study, we used the ArcSWAT (Olivera et al., 2006) program.

The crop growth component of SWAT, is a simplified version of the EPIC model. It can simulate a wide range of crop rotation, grassland/pasture forest systems. Crop growth and yield are governed and limited by temperature, water, nitrogen and phosphorus and other stress factors. Yield is calculated by multiplying the aboveground biomass (bio_{act}) by a harvest index (HI_{act}). The harvest index (HI) is the fraction of above-ground plant dry biomass that is removed from the cultivated land as yield which the biomass also depends on nutrient availability and temperature stress while the harvest index is only affected by water stress. The influence of the latter is subject to calibration. Irrigation and fertilization can be specified by the user or given 'automatically'. In the automatic option, irrigation is applied as soon as water stress threshold is exceeded. Similarly fertilizer is applied depending on a nitrogen stress factor. The total amount of fertilizer applied is specified by the user. We selected automatic irrigation and fertilization option in this study because of the difficulty in obtaining irrigation and fertilization schedule data for different provinces. Plant growth is determined from leaf area development, light interception, and conversion of intercepted light into biomass

assuming a plant-specific radiation use efficiency. A more detailed description of the model is given by Neitsch et al. (2002).

4.2.3 Model parameterization and input data

Spatial parameterization in this project was performed by dividing the country into 506 sub-basins based on topography and dominant soil and landuse. For each unit we simulated four storage volumes: snow, soil, shallow aquifer, and deep aquifer. Surface runoff was simulated using the SCS curve number (CN) method.

Potential evapotranspiration (PET) was simulated using the Hargreaves method. Actual evapotranspiration (AET) was determined using the methodology proposed by Ritchie (1972). Leaf area index (LAI) and root development were simulated on daily time steps. The daily value of LAI was used to partition PET into soil evaporation and plant transpiration. The average number of cumulative heat units was assumed to be around 2300 for wheat (Khodabandeh, 2005). Data for the years 1987-2002 were used for model calibration, using the first 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 we used the data from 1977-1989, again using the first 3 years as warm-up period.

The data required for 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 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 modeling the readers are referred to Faramarzi et al., (2009).

4.2.4 Estimation of crop water productivity (CWP)

The crop water productivity CWP (kg m^{-3}) links water consumption to yield and thus provides an indicator for the value of a unit of water. In this study, it was calculated as:

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

where Y is the annual crop yield (kg ha^{-1}), and ET is the seasonal evapotranspiration ($\text{m}^3 \text{ha}^{-1}$), assumed here to be the crop's consumptive water use.

ET was calculated on a monthly basis. All calculations of Y , ET , and CWP were performed with a sub-basin resolution, but for comparison with other studies and the available statistics, the modeled results were aggregated at the provincial level. It is noteworthy that CWP here does not account for water wasted due to inefficient irrigation.

4.2.5 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 ($AUTO-WSTRS$), nitrogen stress factor ($AUTO-NSTRS$), and planting-harvesting dates. To model the crop yield we calibrated the hydrology (Faramarzi et. al., 2009) followed by calibration of the yield parameters.

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 ranges are based on physically meaningful limits, within which a number of Latin hypercube parameter set samples (McKay et al., 1979) are obtained and simulated for each calibration iteration. Hence, parameters as well as 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. For this purpose, SUFI-2 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. 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:

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

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 range of *RMSE* is 0 to ∞ where 0 is optimal. Thus, the best simulation was considered one with the lowest *RMSE*. The crop yield was simulated at 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).

4.3 Results and discussion

4.3.1 Model results

Table 4.1 summarizes the result of calibration and uncertainty analysis for different provinces for rainfed and irrigated wheat. The 95PPU simulated by SUFI-2

Table 4.1 - 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 |
| Ilam | 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 |
| Kohgiluyeh | 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.

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 to 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 thus a lower uncertainty in the model. The R_m -factor generally ranged between 0.33 and 1.1 for rainfed and from 0.12 to 1.1 for irrigated areas in most provinces. Overall, these statistics indicate that the simulations described wheat yields

quite well with relatively small uncertainties.

For some provinces the simulation did not give good results. For example the R_m -factor was 1.51 for rainfed wheat in Ghom, indicating a large model uncertainty. It could mean that not all relevant processes were adequately accounted for in the model such as particular management practices, for example tillage operation, rotation, water harvesting, supplemental irrigation in rainfed farming, that are used in Iran to increase crop yields. Moreover, 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 4.2 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 Figure 4.3, 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). Figure 4.4 shows that during the calibration period crop yields were within the predicted uncertainty bands for all provinces.

4.3.2 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 in *ET* as well. To test the simulated *ET* against available data, we aggregated the modeled *ET* values to provincial level and compared them with the available data from MOJA (Farshi et al., 1997) (Figure 4.5). Also the simulated *ET* values were related to the water sources, i.e. rain (also referred to as consumptive green water use, *ETG*) and irrigation (also referred to as consumptive blue water use, *ETB*). In order to estimate the contribution of rain to *ET* in irrigated areas, we ran the model first without considering irrigation. Figure 4.5 shows

Table 4.2 - 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: 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 |
| Azarbajan_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 |
| Ilam | 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 |
| Kohiluyeh | 0.38 - 0.41 | 1500 - 2000 | 0.37 - 0.38 | 2100 - 2300 |
| Kordestan | 0.35 - 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.

that MOJA values (total *ET*) are within or very close to the simulated 95PPU *ET*. Some of the discrepancies in this comparison could be explained by the fact that we used the Hargreaves method to calculate *ET*, whereas the MOJA used the Penman-Monteith method (Farshi et al., 1997). Also, the data on planting and harvesting dates and fertilizer used in this study represented long-term averages over the respective province while MOJA used finer resolution sub-provincial information to calculate *ET*. Overall, the comparisons of the modeled and observed yields as well as modeled and previously estimated *ET* indicate that the model described yields as well as hydrology.

As *CWP* has not been calculated before at the sub-basin level and for monthly

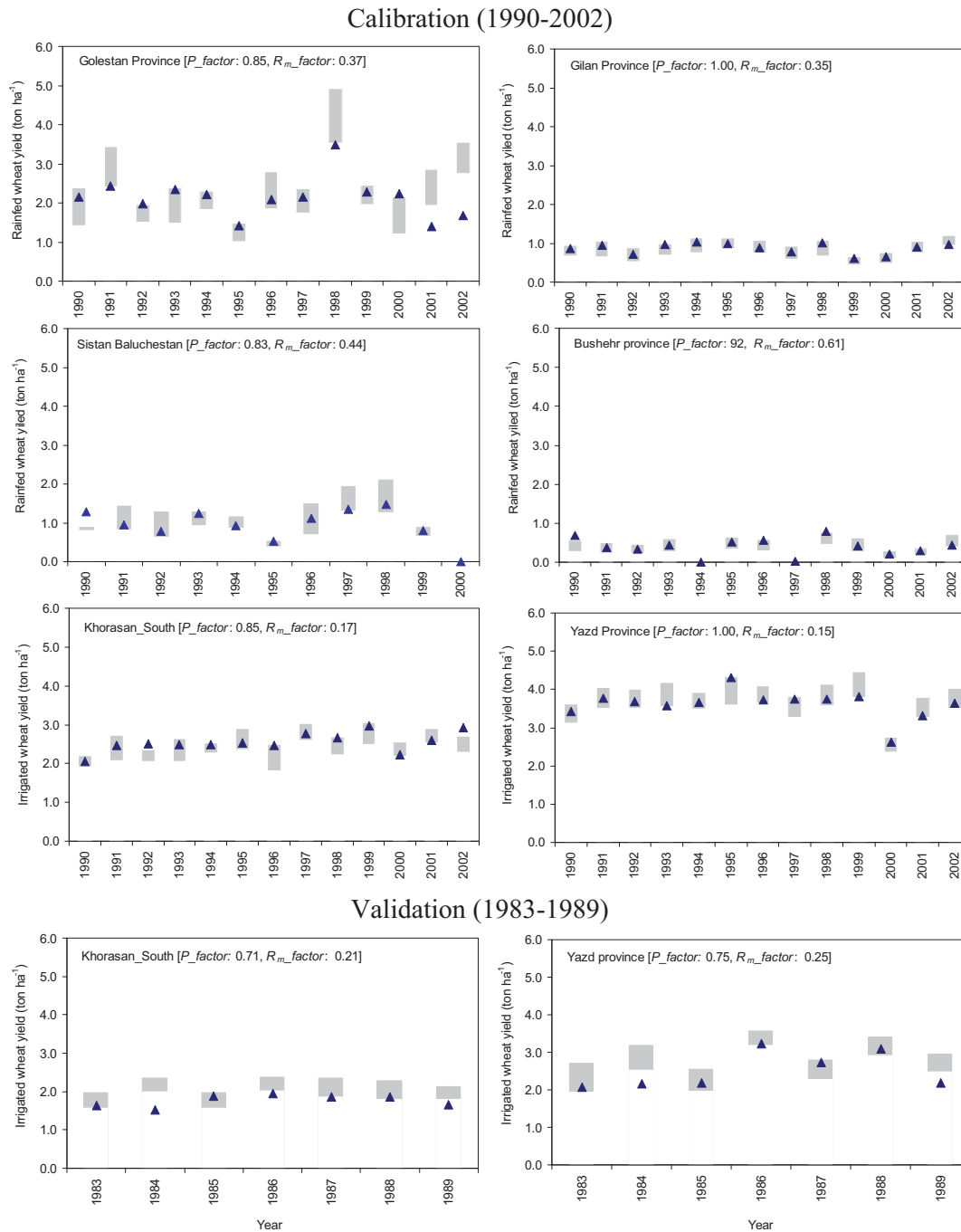


Figure 4.3 - Comparison of observed (blue points) and simulated (expressed as 95% prediction uncertainty band) yield for four selected provinces in rainfed wheat and two provinces in irrigated wheat regions. Calibration and validation results are shown.

time steps in Iran, we aggregated the results to annual and country level in order to compare it to results of other studies. Figure 4.6 compares the national predicted 95PPU of *CWP* (averaged over 1990-2002) with the values published in different sources. Estimation of the country's average *CWP* by Liu et al., (2007), Chapagain and Hoekstra

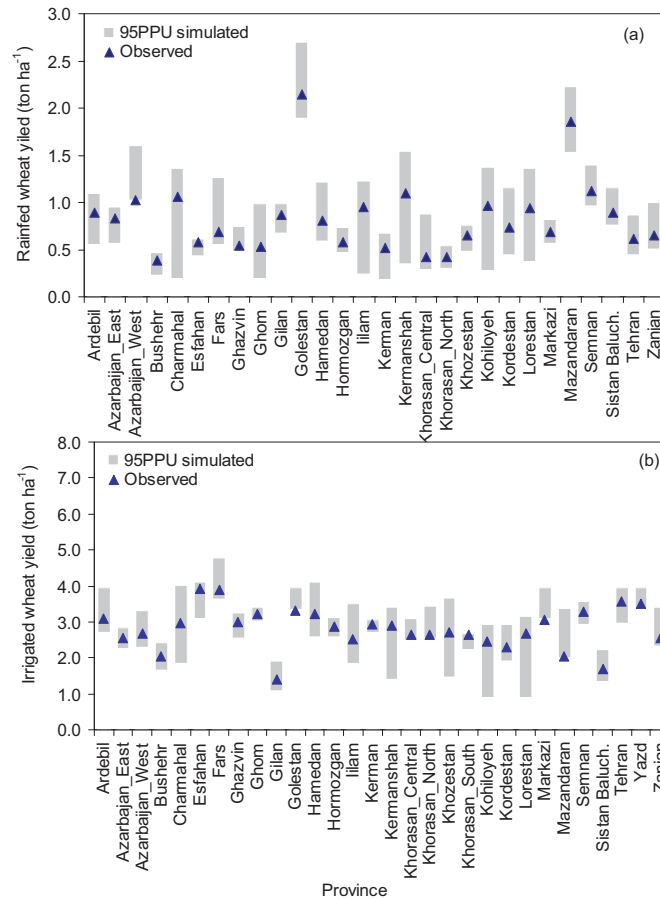


Figure 4.4 - Comparison of the average annual (1990-2002) observed and 95PPU of simulated yield for (a) rainfed and (b) irrigated wheat shown for different provinces.

(2004), and 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 uncertainty band. The estimates given by Chapagain and Hoekstra (2004) are based on climate data obtained from a representative site in a country. Those of Liu et al., (2007) are based on a continuous time series, using a grid based model with a spatial resolution of 30 arc-minute. The *CWP* values reported by SWRI are roughly the average long-term minimum and maximum *CWP* values observed at the country level. A direct one-to-one comparison of these values is not possible because they relate to different time periods and study-specific assumptions. This comparison gives an idea of the differences that exist in *CWP* estimates among different studies. This variation is captured almost entirely in our prediction uncertainty band (Figure 4.6).

The predicted annual (1990-2002) provincial average of *Y*, *ET* and *CWP* are mapped in Figure 4.7. For rainfed wheat, *Y* and *CWP* correlate well, large yields

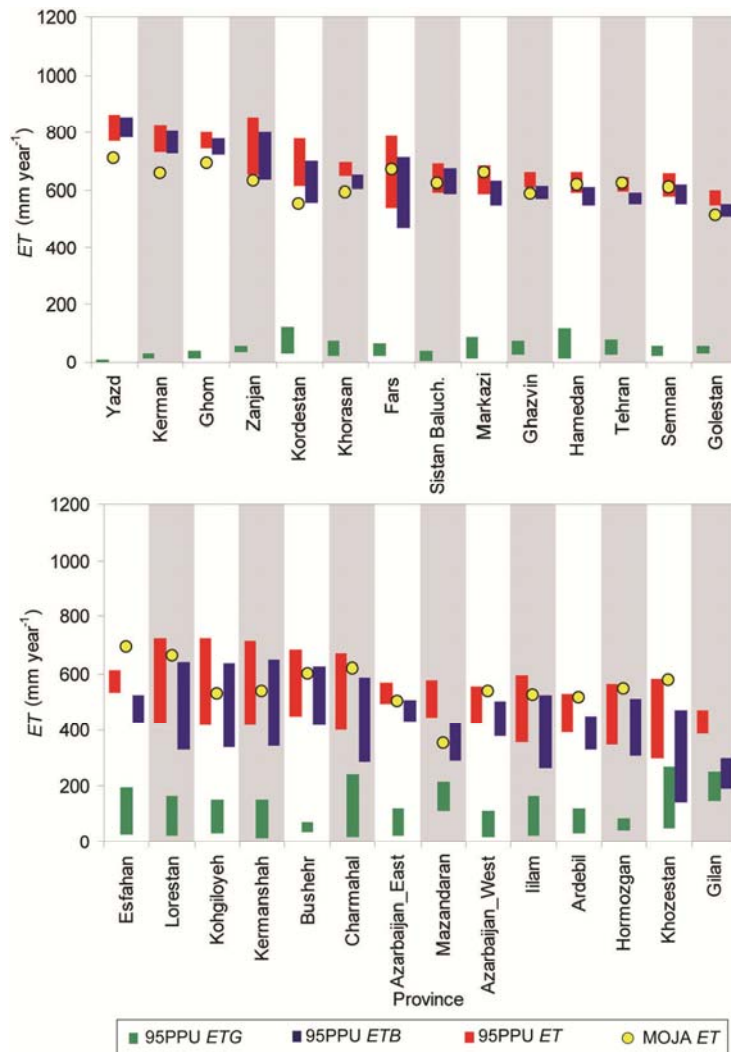


Figure 4.5 -Modeled annual (1990-2002) consumptive water use (ET) expressed as 95%prediction uncertainty band (95PPU), and data obtained from the Ministry of Jahade-Agriculture (MOJA). The modeled data is further divided into precipitation-based (green water) (ETG) or irrigation-based (blue water) ET (ETB).

correspond to large *CWP*. In some southern and northern provinces we found a large *CWP* for rainfed wheat. However, the contributions of *Y* and *ET* in these provinces are quite different. In some southern areas small *Y* resulted in a large *CWP* because also *ET* was low, while in the northern provinces where more water is available a large *CWP* is generally associated with a large crop yield. A comparison of the irrigated (left column) and rainfed (right column) maps in Figure 4.7 illustrates that large irrigated yields were achieved in some provinces where rainfed yield was small. But this doesn't necessarily give a larger *CWP* for irrigated than for rainfed wheat, as also *ET* in irrigated areas is larger than in rainfed areas. Hence, to assess the productive potentials of a region, both

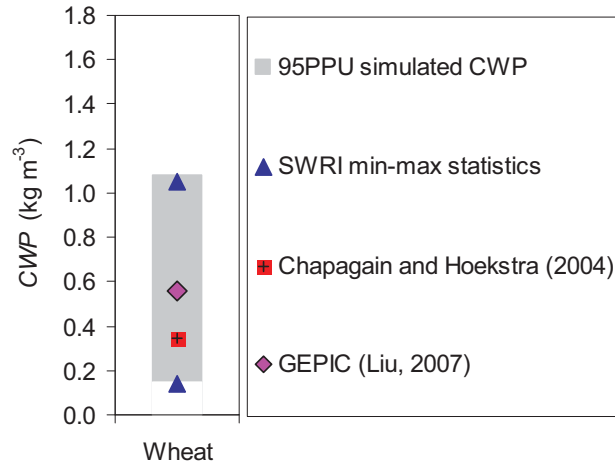


Figure 4.6 - Average annual (1990-2002) 95PPU of modeled CWP at national level and a comparison with the data reported by other sources.

CWP and yield must be considered together.

The temporal variability in CWP, is shown by the box-plots in Figure 4.8. Over all provinces, the variability in CWP was larger for rainfed wheat than for irrigated wheat. Furthermore, Figure 4.8 shows that under rainfed as well as irrigated conditions the variability tended to increase with increasing CWP. A smaller variability with irrigated may be expected, as the production of irrigated wheat is rather consistent due to a more controlled agricultural condition across all the provinces.

4.3.3 Yield-ET-CWP relations

The relationship between wheat yield and ET is shown in Figure 4.9a. 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 of 3 ton ha⁻¹ for irrigated land, and from 0 to 4.32 ton ha⁻¹ with an average of 0.91 ton ha⁻¹ for rainfed land. ET varied from 399 mm to 910 mm for irrigated wheat and from 0 to 386 mm for rainfed wheat. Also CWP increased with yield, but differently for rainfed and irrigated agriculture (Figure 4.9b). In rainfed wheat, CWP increased stronger with yield than in irrigated wheat. This means that a unit increase in water resulted in a larger additional yield increase in rainfed than in irrigated wheat. The results suggest that rainfed yield is more responsive to additional water. The inference is that 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

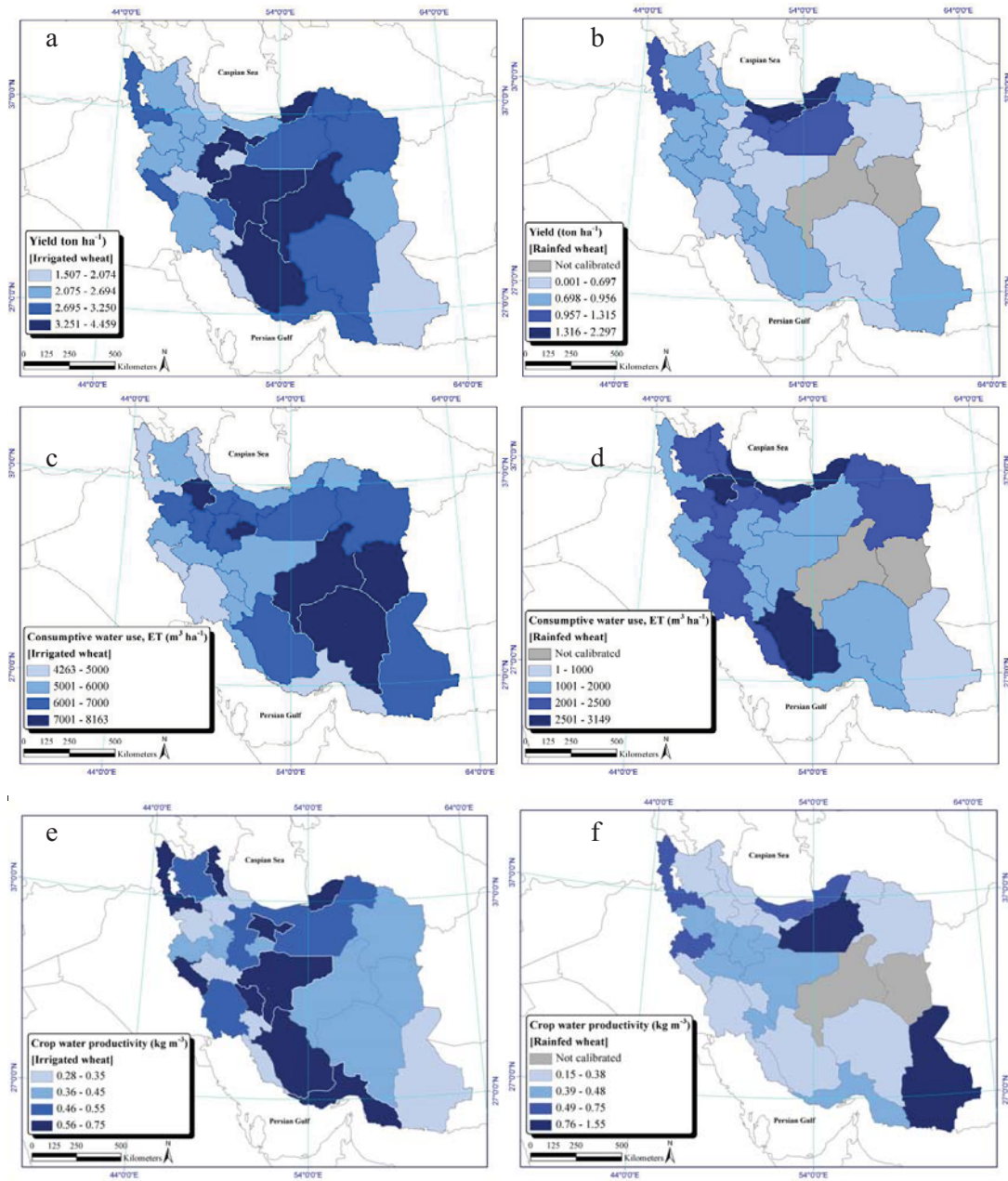


Figure 4.7 - The predicted average annual (1990-2002) yield, consumptive water use, and crop water productivity of rainfed (right) and irrigated (left) wheat for different provinces.

al. (2007) who found that in the smaller yield range ($< 3 \text{ ton ha}^{-1}$) less incremental water is required to increase 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 scarcity management, as suggested by Falkenmark (2007), may be a way of dealing with water scarcity.

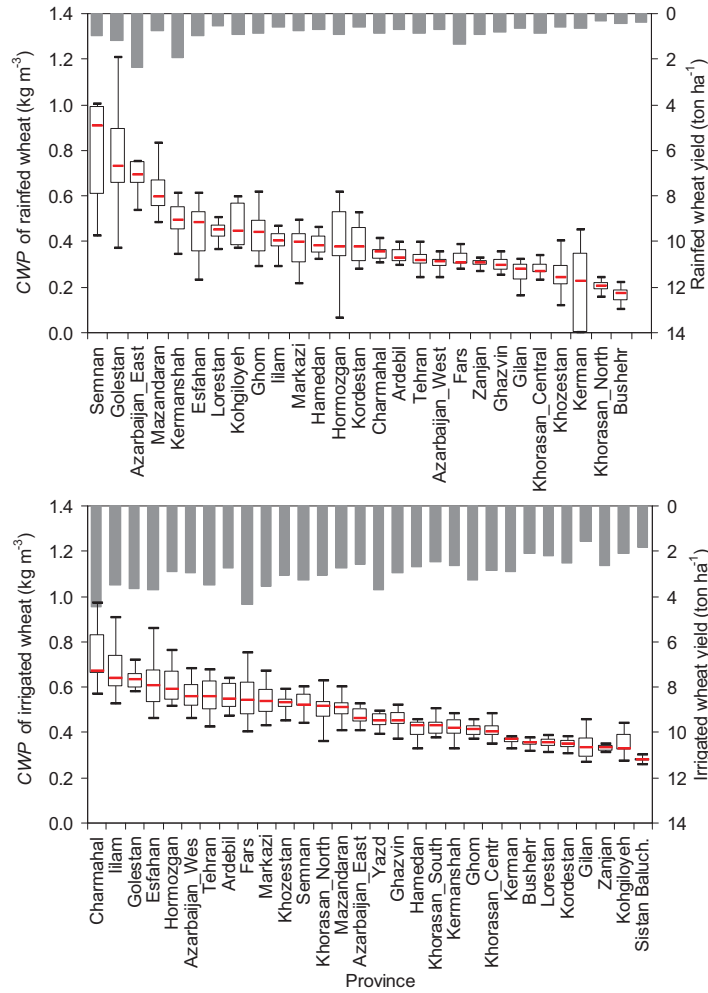


Figure 4.8 - Simulated rainfed and irrigated wheat CWP of different provinces. The annual (1990-2002) values are used to show the dispersion and skewness in the box-plots for each province.

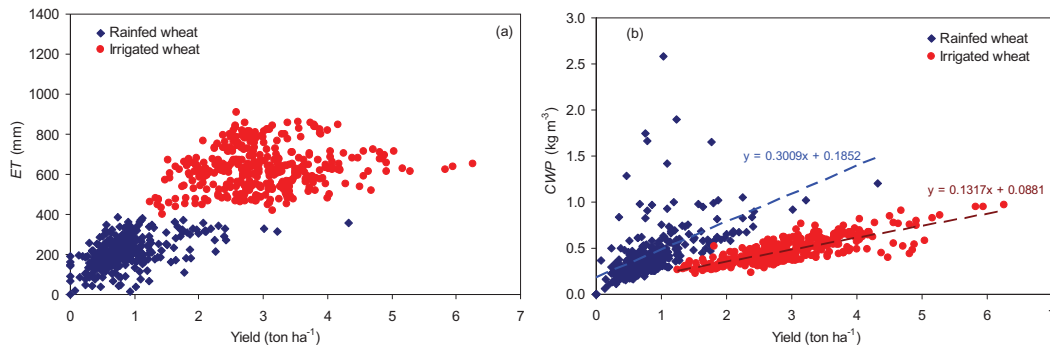


Figure 4.9 - Y-ET and CWP-Y relationships for (a) rainfed and (b) irrigated wheat. Data are from all provinces.

4.4 Assessing different water management policies

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 potential strategies.

4.4.1 Assessment of irrigation application

To observe more clearly the Y - CWP relation for rainfed and irrigated wheat in individual provinces, we constructed Table 4.3. This table shows the potential improvement in yield and CWP when shifting from rainfed to irrigated conditions. It can be seen that in all provinces wheat yields would increase with such a shift. In the first 11 provinces CWP would increase substantially ($> 50\%$). In the middle 7 provinces (highlighted with underline), CWP increases in the range of 0 to 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. Limitation here is most likely due to temperature. A case by case study of the provinces is, therefore, required for

Table 4.3 - 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 |
| Boshehr | 0.36 | 0.15 | 477 | 138 |
| Khozestan | 0.63 | 0.25 | 386 | 112 |
| Charmahal | 0.67 | 0.36 | 561 | 108 |
| Ilam | 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 |

a deeper understanding of the *Y-ET-CWP* relationship.

4.4.2 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. Figure 4.10 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 4.4 lists six provinces with irrigated wheat and four provinces with rainfed wheat in the country that have the potential to achieve a larger yield and *CWP* if more fertilizer is applied. The improvement in *CWP* in these provinces is mostly due to the increase in yield, while *ET* remains almost unchanged. These provinces cover, 13% and 14% of the irrigated and rainfed wheat-cultivated-areas in the country, respectively. Using the simulated annual (1990-2002) average wheat yield with and without additional fertilization, we computed the potential gain in 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.

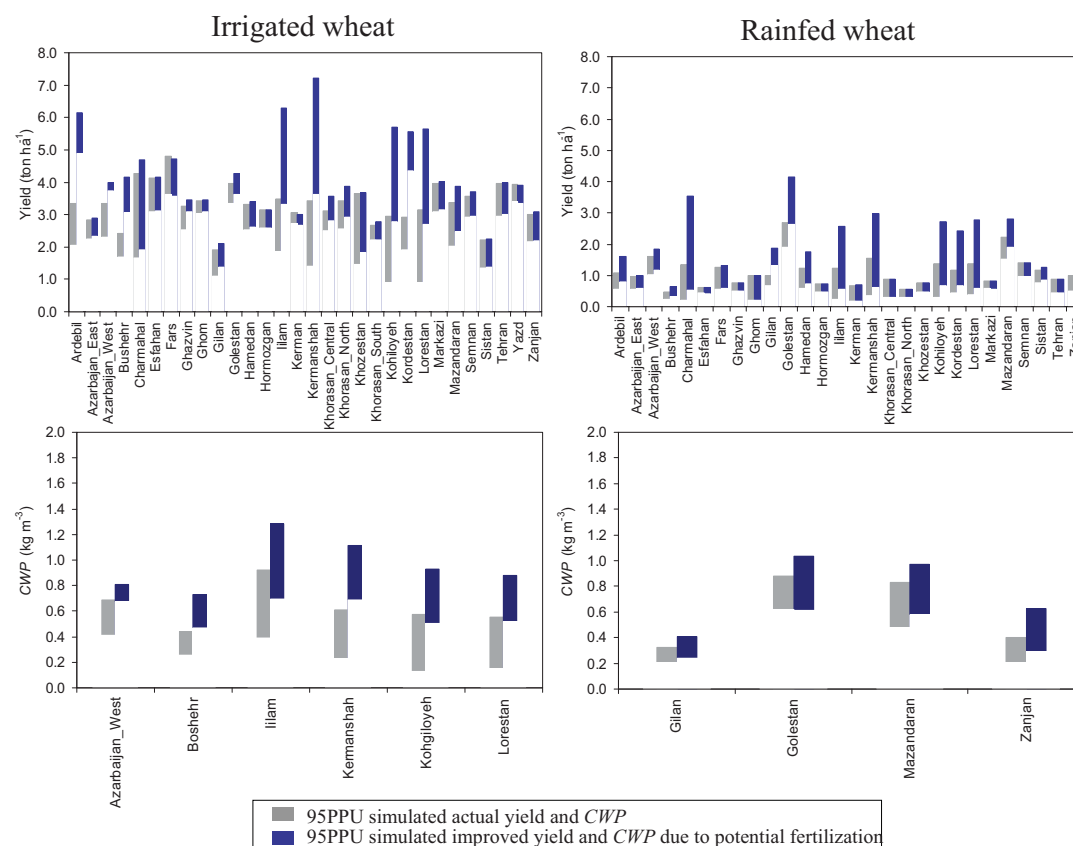


Figure 4.10 - Scenario analysis for potential fertilizer-use. 95PPU of average annual (1990-2002) wheat yield, and *CWP* under irrigated and rainfed conditions for actual (historical) and potential fertilizer use scenarios.

Table 4.4 - 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 potential production with no fertilizer limitation. Only the provinces that benefit from production increase with more fertilizer application are considered.

| 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_W | 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 |
| Ilam | 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 |
| Kohiluyeh | 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.

4.4.3 Assessment of improvement 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 soil quality is one of the major limiting factors in crop production. Proper soil management practices are usually urged by policy makers for sustainable agriculture. However, their impact on water use is usually not known. Therefore we quantified 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 the other parameters unchanged. The results 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 (Figure 4.11). A simple calculation shows that around (1.54-2.07) km³ of irrigation water could be saved annually, which is about 5-6% of the total irrigation water use for wheat, at present.

4.4.4 Assessment of water use sustainability

Given increasing water use due to population growth and economic development, a trend of decreasing water availability, there is an urgent need to balance water supply and demand in Iran. Figure 4.12a illustrates the ratio of irrigation water requirement (*IWR*) to the internal renewable blue water availability (*IRWR*) for 18 main crops across the provinces.

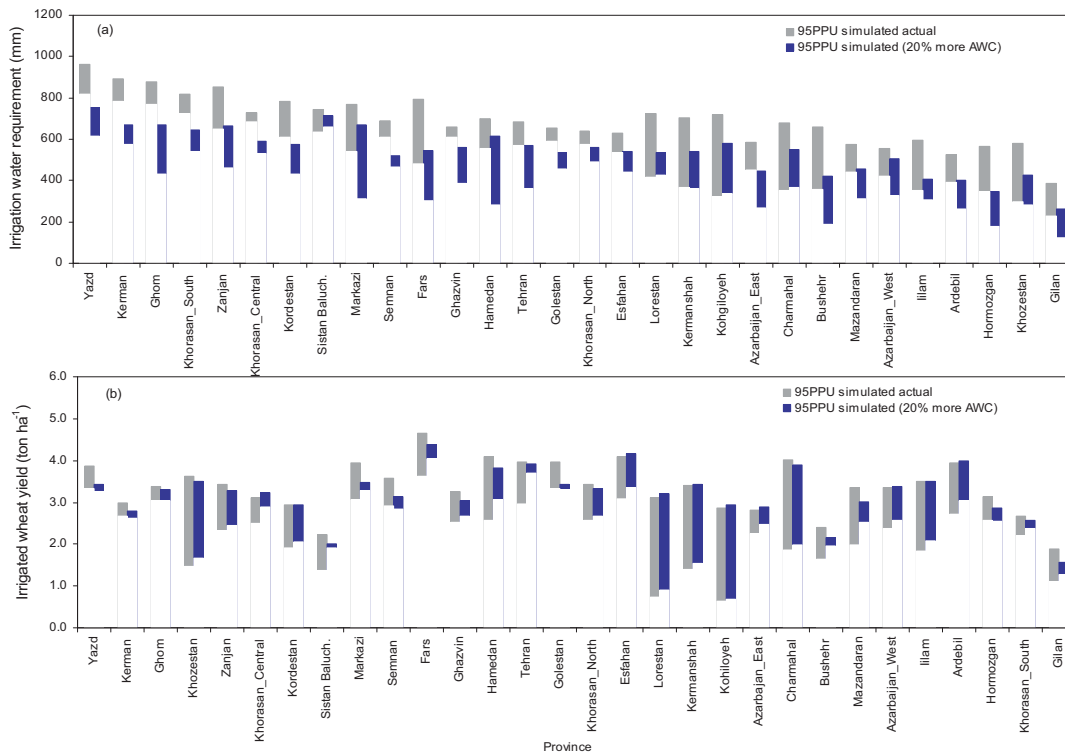


Figure 4.11 - Scenario analysis for increased available water capacity (AWC). (a) 95PPU of irrigation requirement, and (b) average annual (1990-2002) wheat yield under actual (historical) and 20% more AWC scenarios.

In 21 provinces this ratio is more than 40% (Table 4.5). These provinces are “water scarce” according to an index proposed by Raskin et al. (1997) and Alcamo et al. (2007). In 12 provinces 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 groundwater over-extraction and climate-change induced droughts, groundwater 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 most provinces for future irrigated agricultural production, especially for wheat production. The above calculation of *IWR* is based on the 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 would be reduced, we plotted Fig. 12b based on the consumptive blue water use (*ETB*), which does not include any water losses. It can be seen that 12 provinces still have a ratio of *ETB* to blue water availability above 40% and in four provinces the ratio is still exceeding 100%. Table 4.5 quantifies in detail provincial *IRWR*, *IWR*, *ETB*, and the water scarcity ratios for all provinces.

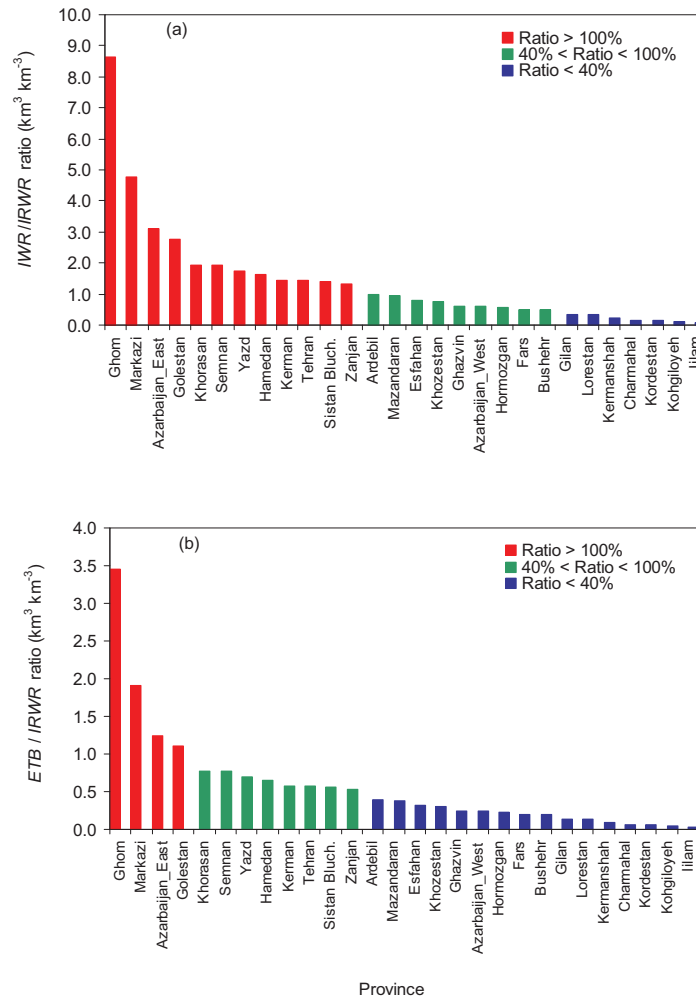


Figure 4.12 - Ratio of provincial water use (*ETB*) to water availability (expressed as internal renewable water resources, *IRWR*, data from Faramarzi et al., 2009) based on the average of (1990-2002) data. Data for provincial water use are calculated for 18 main crops across the provinces. Data of all crops were obtained from Farshi et al. (1997), except for wheat and barley, for which *IWR* was calculated in this study.

After 45 years of importing wheat, 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% were 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, using large variant, medium variant, and small variant population scenarios according to the United Nation's population prediction (<http://esa.un.org/unpp/index.asp>). Other factors were kept as they were in 2004 including the per capita production distribution and *CWP*. To estimate

Table 4.5 - 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.

| 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 |
| Ilam | 3.929 | 0.343 | 0.137 | 0.087 | 0.035 | 0.078 | 0.085 |
| Kohgiluyeh | 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. The highlighted values in table show the water scarce provinces with higher scarcity index in the future than historic.

the provincial production for the year 2020, we distributed the national production according to contributions of the provinces to today's wheat production, using the data on irrigated wheat production.

The last two columns of Table 4.5 show the water needed to produce wheat to fully meet the expected demand in 2020 without wheat import. In the last column water scarce provinces are highlighted where consumptive blue water demand for wheat is

larger than what was required in the past.

Figure 4.13 shows that in 13 provinces the average ET will be significantly higher in 2020 than in 2004. Moreover, 88% of the increase in production will come from the provinces that already have a water scarcity ratio above 40% (e.g. Ghom, Semnan, Yazd, Sistan, Tehran, Ghazvin, Kerman, Khorasan, Esfahan, and Markazi) according to our calculations. At the national level, the required ET for wheat was estimated to be 16-27

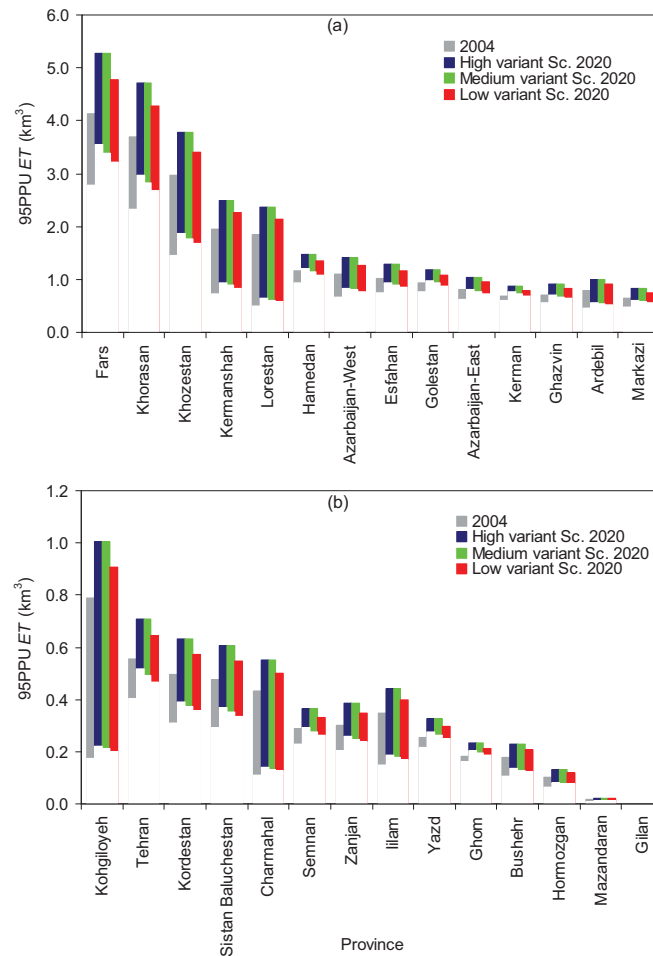


Figure 4.13 - Scenario analysis for water demand for irrigated wheat to maintain self-sufficiency in 2020. The medium variant population scenario shows a significant increase in consumptive water use in all provinces.

$\text{km}^3 \text{ year}^{-1}$ in 2004. In 2020 respective estimates are 18-31, 19-34, and 20-34 $\text{km}^3 \text{ year}^{-1}$ for low, median, and high population scenarios. This means that the above provinces would face serious water shortages, threatening the long-term food security of the country. The situation becomes even more critical when we consider the poor water resources management and the low irrigation efficiency in Iran, as well as the predicted

increase in droughts frequency and severity due to climate change (Abbaspour et al., 2009). Therefore, the question of where the needed water will come from, urges a serious re-consideration of the current agricultural production strategy in Iran.

4.5 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*.

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 3) 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.

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 the *AWC* through proper soil management practices. Taking the average 95PPU of the modeled irrigation in the improved *AWC* scenario, we calculated that (1.54-2.07) km³ 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 5). 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.

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References

- Abbaspour, K.C., 2007. User Manual for SWAT-CUP, SWAT Calibration and Uncertainty Analysis Programs, Swiss Federal Institute of Aquatic Science and Technology, Eawag, Duebendorf, Switzerland.
- Abbaspour, K.C., Faramarzi, M., Seyed Ghasemi, S., Yang, H., 2009. Assessing the impact of climate change on water resources of Iran. *Water Resour. Res.* In press.
- Abbaspour, K.C., Johnson, A., van Genuchten, M. Th., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone J.* 3, 1340-1352.
- Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., Srinivasan, R., 2007. Modelling hydrology and water quality in the pre-Alpine/Alpine Thur watershed using SWAT. *J. Hydrol.* 333, 413-430.
- Aggarwal, P.K., Kalra, N., Chander, S., Pathak, H., 2006. InfoCrop: A dynamic simulation model for the assessment of crop yield, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agr. Syst.* 89, 1-25.
- Akbari, M., Toomanian, N., Droogers, P., Bastiaanssen, W., Gieske A., 2007. Monitoring irrigation performance in Esfahan, Iran, using NOAA satellite imagery. *Agr.*

- Water Manage. 88, 99-109.
- Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rosch, T., Siebert, S., 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrolog. Sci. J.* 48(3), 317-337.
- Alcamo, J., Flörke, M., Märker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrolog. Sci. J.* 52(2), 247-275.
- Alizadeh, A., Keshavarz, A., 2005. Status of agricultural water use in Iran. In: NRC, National Research Council, Water conservation, reuse, and recycling: Proceeding of an Iranian American workshop. The National Academies Press: Washington, D.C, pp. 94-105.
- Ardakanian, R., 2005. Overview of water management in Iran. In: NRC, National Research Council, Water conservation, reuse, and recycling: Proceeding of an Iranian American workshop. The National Academies Press: Washington, D.C, pp. 18-33.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment - Part 1: Model development. *J. Am. Water Resour. As.* 34(1), 73-89.
- Banaei, M.H., Moameni, A., Bybordi, M., Malakouti, M.J., 2005. The Soils of Iran: New Achievements in Perception, Management and Use. Soil and Water Research Institute Press, Tehran, Iran (in Persian).
- Bessembinder, J.J.E., Leffelaar, P.A., Dhindwal, A.S., Ponsioen, T.C., 2005. Which crop and which drop, and scope for improvement of water productivity. *Agr. Water Manage.* 73(2), 113-130.
- Challinor, A.J., Wheeler, T.R., 2008. Crop yield reduction in the tropics under climate change: processes and uncertainties. *Agric. For. Meteorol.* 148(3), 343-356.
- Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. In: Value of Water Research Report Series No. 16, vlos. 1-2, UNESCO-IHE, Delft, the Netherlands.
- Dehghani, S.H., Alizadeh, A., Keshavarz, A., 1999. Implementation of Water Use Pattern in Terms of Volumetric Supply of Water to Farmers. Iranian Agricultural Research Institute (IAERI) Press, Tehran, Iran (in Persian).
- Deihimfard, R., Zand, E., Mahdavi Damghani, A., Soufizadeh, S., 2007. Herbicide risk assessment during the wheat self-sufficiency project in Iran. *Pest. Manag. Sci.* 63(10), 1036-1045.

- Falkenmark, M., 2007. Shift in thinking to address the 21st century hunger gap Moving focus from blue to green water management. In: *Integrated Assessment of Water Resources and Global Change*, edited by E. Craswell, M. Bonnell, D. Bossio, S. Demuth, and N. VandeGiesen, pp. 3-18.
- FAO, 2002. General status of the food and agricultural statistics in Iran, In: *Improvement of Agricultural Statistics in Asia and Pacific Countries*, (GCP/RAS/171/JPN), Bangkok.
- FAO, 2005. *Fertilizer Use by Crop in the Islamic Republic of Iran*. Rome, Italy.
- Faramarzi, M., Abbaspour, K.C., Schulin, R., Yang, H., 2009. Modelling blue and green water resources availability in Iran. *Hydrol. Process.* 23(3), 486-501.
- Farshi, A.A., Shariati, M.R., JaroLlahi, R., Ghaemi, M.R., Shahabifar, M., Tavallaei, M.M., 1997. *An Estimate of Water Requirement of Main Field Crops and Orchards in Iran*. Ministry of Agriculture, Agricultural and Natural Resource Organization, Water and Soil Research Institute Press, Karaj, Iran (in Persian).
- Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Trans. ASABE* 50, 1211-1250.
- Ghafouri, M., 2007. *Extended Abstracts of International workshop on Improving Water Productivity and Livelihood Resilience in Karkheh River Basin*. MOJA-AREO-CGIAR challenge program-ICARDA, Karaj, Iran.
- Iizumi, T., Yokozawa, M., Nishimori, M., 2009. Parameter estimation and uncertainty analysis of a largescale crop model for paddy rice: application of a Bayesian approach. *Agric. For. Meteorol.* 149(2), 333-348.
- Keshavarz, A., Ashrafi, S., Hydari, N., Pouran, M., Farzaneh, E., 2005. Water allocation and pricing in agriculture of Iran, In: *NRC, National Research Council, Water conservation, reuse, and recycling: Proceeding of an Iranian American workshop*. The National Academies Press: Washington, D.C, pp. 153-172.
- Khodabandeh, N., 2005. *Cereals*. Tehran Univ. Press, Tehran, Iran (in Persian).
- Kijne, J.W., Barker, R., Molden, D., 2003. *Water Productivity in Agriculture: Limits and Opportunities for Improvemen*, In: *Comprehensive Aassessment of Water Management in Agriculture*, Series 1, CAB7IWMI, Wallingford, UK.
- Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. *Agr. Syst.* 94(2), 478-493.

- McKay, M.D., Beckman, R.J., Conover, W.J., 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics* 21(2), 239–245.
- Molden, D., 1997. Accounting for water use and productivity. SWIM paper Vol.1, International Irrigation Management Institute, Colombo, Sri Lanka.
- Mousavi, S.F., 2005. Agricultural drought management in Iran. In: NRC, National Research Council, Water conservation, reuse, and recycling: Proceeding of an Iranian American workshop. The National Academies Press: Washington, D.C, pp. 106-113.
- NCCO, 2003. Initial National Communication to United Nations Framework Convention on Climate Change. Published by Iranian National Climate Change Office at Department of Environment, Tehran, Iran.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2002. Soil and Water Assessment Tool. Theoretical documentation: Version 2000, TWRI TR-191, College Station, Texas: Texas Water Resources Institute.
- NRC, National Research Council, 2005. Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop. Committee on US-Iranian Workshop on Water Conservation and Recycling, The National Academic Press, Washington, D.C.
- Olivera, F., Valenzuela, M., Srinivasan, R., Choi, J., Cho, H.D., Koka, S., Agrawal, A., 2006. ArcGIS-SWAT: A geodata model and GIS interface for SWAT. *J. Am. Water Resour. As.* 42(2), 295-309.
- Pazira, E., Sadeghzadeh, K., 1999. Sustainable soil and water use in agricultural sector of Iran. In: Proceedings of 99 international conference on agricultural engineering, Beijing, China.
- Raskin, P., Gleick, P., Kirshen, P., Pontius, G., Strzepek, K., 1997. Water Futures: Assessment of Long-range Patterns and Prospects. Stockholm Environment Institute, Stockholm, Sweden.
- Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8, 1204-1213.
- Rockstrom, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: the potential of green water for increasing resilience to global change. *Water Resour. Res.* 45, W00A12.

- Rockstrom, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. *Proc. Natl. Acad. Sci. U.S.A.* 104, 6253–6260.
- Ruget, F., Brisson, N., Delecolle, R., Faiver, R., 2002. Sensitivity analysis of a crop simulation model, STICS, in order to choose the main parameters to be estimated. *Agronomie* 22(2), 133-158.
- Salemi, H.R., Mamanpoush, A., Miranzadeh, M., Akbari, M., Torabi, M., Toomanian, N., Murray-Rust, H., Droogers, P., Sally, H., Gieske, A., 2000. Water Management for Sustainable Irrigated Agriculture in Zayandeh Rud Basin, Esfahan Province, Iran, IWMI-IAEIR, Iran.
- Seckler, D., Amrashinghe, U., Molden, D., de Silva, R., Barker, R., 1998. World Water Demand and Supply, 1990-2025: Scenarios and Issues. Research Report No. 19, International Water Management Institute, Colombo, Sri Lanka.
- Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K., 2007. Global Map of Irrigation Areas version 4.0.1., Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy.
- Singh, R., van Dam, J.C., Feddes, R.A., 2006. Water productivity analysis of irrigated crops in Sirsa district, India. *Agr. Water Manage.* 82(3), 253-278.
- USDA, 2003. Production Estimates and Crop Assessment Division. Foreign Agricultural Service,
http://www.fas.usda.gov/pecad2/highlights/2003/12/iran_dec2003/index.htm.
- Vazifedoust, M., van Dam, J.C., Feddes, R.A., Feizi, M., 2007. Increasing water productivity of irrigated crops under limited water supply at field scale. *Agr. Water Manage.* 95(2), 89-102.
- Wang, X., Williams, J.R., Izaurrealde, R.C., Atwood, J.D., 2005. Sensitivity and uncertainty analysis of crop yields and soil organic carbon simulated with EPIC. *Transactions of the ASAE* 48(3), 1041-1054.
- Yang, H., Reichert, P., Abbaspour, K.C., Zehnder, A.J.B., 2003. A water resources threshold and its implications for food security. *Environ. Sci. Technol.* 37(14), 3048-3054.
- Yang, H., Zehnder, A., 2007. “Virtual water”: An unfolding concept in integrated water resources management. *Water Resour. Res.* 43, W12301.

Ziaei, A., Sepaskhah, A.R., 2003. Model for simulation of winter wheat yield under dryland and irrigated conditions. *Agr. Water Manage.* 58(1), 1-17.

HYDROLOGY AND EARTH SYSTEM SCIENCES 14: 1417-1433 2010**5 ANALYSIS OF INTRA-COUNTRY VIRTUAL WATER TRADE TO ALLEVIATE WATER SCARCITY IN IRAN**

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Abstract

Increasing water scarcity has posed a major constraint to sustain food production in many parts of the world. To study the situation at the regional level, we took Iran as an example and analyzed how an intra-country “virtual water trade strategy” (VWTS) may help improve cereal production as well as alleviate the water scarcity problem. This strategy calls, in part, for the adjustment of the structure of cropping pattern (ASCP) and interregional food trade where crop yield and crop water productivity as well as local economic and social conditions are taken into account. We constructed a systematic framework to assess ASCP at the provincial level under various driving forces and constraints. A mixed-integer, multi-objective, linear optimization model was developed and solved by linear programming. Data from 1990-2004 were used to account for yearly fluctuations of water availability and food production. Five scenarios were designed aimed at maximizing the national cereal production while meeting certain levels of wheat self-sufficiency under various water and land constraints in individual provinces. The results show that under the baseline scenario, which assumes a continuation of the existing water use and food policy at the national level, some ASCP scenarios could produce more wheat with less water. Based on different scenarios in ASCP, we

calculated that 31% to 100% of the total wheat shortage in the deficit provinces could be supplied by the wheat surplus provinces. As a result, wheat deficit provinces would receive 3.5 bcm to 5.5 bcm of virtual water by importing wheat from surplus provinces.

Keywords: virtual water trade strategy, water scarcity, adjustment in structure of cropping pattern, optimization procedure, linear modeling.

5.1 Introduction

Population growth and industrialization on the one hand and extended drought, environmental concerns, and a possible adverse impact of climate change on the other hand are the major limiting factors on water resources threatening food security in developing countries of arid and semi-arid regions. With no significant room to expand cultivation areas in these regions, increased demand for food will have to be met through sustainable agricultural production, which entails improved management of the available resources and development of crop production strategies [Qadir, *et al.*, 2007], as well as import from outside [Yang *et al.*, 2006; Allan, 1997].

Large parts of Iran are characterized as arid and semi-arid environment. The country is enduring increasing water scarcity, which has posed a major constraint to the expansion of crop land and food production. Agriculture is by far the largest water user in Iran, accounting for more than 90% of the total water withdrawal. Despite the scarce water resources availability, wheat self-sufficiency has long been an important national goal, which was temporarily achieved in 2004. However, there is a general doubt about Iran's ability to maintain this level of production amid the mounting water challenges, among other obstacles. In general, the agricultural water use efficiency is low in Iran. The average irrigation and conveyance efficiency is around 36% at the national level. For many provinces, the efficiency can be as low as 15%. Main reasons for low efficiency are improper design of irrigation facilities, poor maintenance, careless operation, negligible water pricing as well as inefficient division of responsibilities among different agencies [Pazira, *et al.*, 1999, Kehsavarz *et al.*, 2005]. Efforts to increase the agricultural water use efficiency have been made through increasing crop water productivity (*CWP*) at plant and field levels [Ardakanian, 2005]. But this has not so far alleviated the water scarcity problem, as in many areas the situation has been worsening.

Facing the sober challenges, there have been renewed calls and efforts from the government of Iran to improve water resources management and plans to mitigate water scarcity. The long term policies are to invest on water projects, exploit new water resources, and investigate the benefits from adjustment of structure of cropping pattern (ASCP) to deal with the growing water shortages [National Research Council, *NRC*, 2005; The 5th World Water Forum by Iranian Ministry of Energy, 2009]. So far, however, bulk of the investment is allocated for harnessing and regulating water

resources via construction of dams, water transfer projects, and building irrigation networks

[http://icerik.worldwaterforum5.org/files/ThematicDocuments/SessionDocuments/18_03_2009/Ayvansaray/]. Little effort has so far been made in developing a strategy for ASCP.

Iran currently has 19 million ha of agricultural land, accounting for 12% of the total area of the country. Of the total agricultural land, over 60% is devoted to wheat, 20% to barley, 5% to rice, 2% to maize and the rest of the land is covered by other crops. Cereals are the largest user of irrigation water. Of the total water diverted to irrigate cereal crops, wheat uses more than 70%. This amount of water exceeds the internal renewable water resources availability in many provinces located in central dry regions. Therefore, a large amount of water is extracted from fossil groundwater or water transfer projects to meet the water demand. It was found by *Faramarzi et al.* [2009] that about 53% of the area under cultivation of wheat in Iran is located in water scarce sub-basins. Of the total wheat production (10.83 million tons) in the country, 4.4 million tons of irrigated wheat and 1.9 million tons of rain-fed wheat are produced every year in water scarce regions. This has a significant implication for future agricultural food production.

The virtual water trade (VWT) introduced by *Allan* [1997] has been seen as one of the ways to improve water use efficiency and to mitigate water scarcity at the regional level through ASCP and interregional food trade [*Chapagain, et al., 2006; Yang, et al., 2006*]. What we refer to as “virtual water trade strategy” (VWTS) in this paper involves adjustment of the structure of cropping pattern and interregional food trade where crop yield and crop water productivity, national food production objectives, as well as local economic and social conditions are taken into account as discussed in section 5.2.2.

VWT has so far been mainly studied in the arena of international trade. A set back in developing a clear VWTS internationally has been the exercise of trade sanctions imposed on importing countries at will. This although did not stop VWT, it had the effect of deterring the countries from formulating clear and long-term VWT strategies as an effective policy option for combating local water scarcities. The principles of VWT are also applicable within a country like Iran where there are lesser political barriers in inter-provincial trades and significant regional variations in climate, resources and crop production. In such a situation, water resources can be used more efficiently at the national level if crops are produced in the regions/provinces where crop water productivity is large and exported to the regions where the crop water productivity is

small. However, any change in cropping structure is subject to many factors ranging from natural resources, ecological, socio-economic, and institutional conditions. Hence, there is a need for a systematic framework to support the policy makers in the planning of the structure of regional cropping pattern to meet certain national goals of food production while taking into consideration these constraints. Based on the best of our knowledge, so far such a study has not been seen in the virtual water literature. The current study is a novel step to develop a systematic framework for implementing VWTS in Iran through ASCP.

Improving the water resources management through ASCP can be formulated as a multi criteria analysis problem and solved by optimization methods. In the literature there are different techniques dealing with multi criteria analysis problems. Very broadly they can be grouped into two categories: participatory based decision making processes and non-participatory based optimization techniques. The first category includes methods such as: multiple-criteria utility functions [e.g. *Prato and Herath, 2007*], analytical hierarchy process (AHP) [e.g. *Mau-Crimmins et al., 2005*], and Electre [e.g. *Kangas et al., 2002; Figueria and Roy, 2002*]. In the second category, the techniques of linear programming [*Makowski et al., 2000*], genetic algorithms [*Ines et al., 2006*], meta modeling [*Mousavi and shourian, 2009*], and goal programming [*Foued and Sameh, 2001; Agha, 2006; Al-Zahrani and Ahmad, 2004; Yang and Abbaspour, 2007*] are more widely used. The first category might not be relevant in this study because it is interview based and calls for direct participations of decision makers and other stakeholders. As our project is large scale with multiple criteria, the second category would be more suitable to apply. In the second category, goal programming is one of the popular multi-criteria optimization techniques used for water resources management and planning. It provides a way of considering more than one objective function. It sets a specific numeric goal for each objective, and then seeks a solution that maximizes the weighted sum of objectives while taking a set of constraints into consideration.

The current study is an integral part of a larger project aimed to assess the feasibility of applying intra-country VWTS to alleviate water scarcity in a systematic manner. In the first step of the project, the Soil and Water Assessment Tool (SWAT) [*Arnold, et al., 1998*] was used to quantify the water resources availability at sub-basin spatial and monthly temporal resolutions in Iran [*Faramarzi, et al., 2009*]. In the second step of the project, we modeled the sub-basin based crop yield (y), consumptive water use (ET), and crop water productivity (CWP) in different provinces. The likely effects of

some policy options concerning field level management were investigated [Faramarzi, *et al.*, 2010]. The results suggested that Iran is unlikely to meet its national food objectives by merely implementing measures concerning improving field level management. Built upon the results of the previous two works, this study assesses the feasibility of applying VWTS as a policy instrument to alleviate regional water scarcity while maintaining certain level of cereal production and self-sufficiency in wheat in Iran.

Against this background, this study intends to address the following questions: i) how to construct a systematic framework to assess the provincial ASCP and cereal production corresponding to VWTS; ii) what are the optimum sizes of areas under cereal crops across different provinces to maximize national cereal production, while meeting a certain level of wheat self-sufficiency and water scarcity in Iran; iii) what will be the impact of improved irrigation efficiency on wheat self-sufficiency, cereal production, and water scarcity alleviation; and iv) what are the implications of ASCP for intra-country virtual water trade and physical water transfers in Iran. The reason for focusing on water in this study is that water scarcity has become a major constraint in many provinces in Iran. The impact of climate change was shown to exasperate the water problems in Iran [Abbaspour, *et al.* 2009]. The rapid depletion of water resources in many provinces has posed a threat to the future food production. This means that the trend in water use in these provinces can not be continued without facing serious ecological and economic consequences. Measures to halt the water resource over exploitation and depletion have to be sought to prevent the situation to slide over to the point of no return. The reason for focusing on cereal crops, particularly wheat, is because of their strategic importance for food security. Maximizing cereal production is of the national interest while achieving wheat self-sufficiency is the desired national goal in Iran.

5.2 Materials and methods

5.2.1 Study area

Geographically, Iran is located between 25 - 40 degrees north latitude and 44 - 63 degrees east longitude with total area of about 1.648 million km². 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. The country-wide average precipitation is about 252 mm year⁻¹. The northern and high altitude areas in the west receive about 1600-2000 mm year⁻¹ [NCCO, 2003], while the

central and eastern parts of the country receive less than 120 mm year⁻¹. The per capita freshwater availability for the country was estimated at around 2000 m³capita⁻¹year⁻¹ in the year 2000 and expected to go below 1500 m³capita⁻¹year⁻¹ by 2030 due to population growth [Yang *et al.*, 2003]. Winter temperatures of less than -20 °C in high altitude of the country and summer temperatures of more than 50 °C in some areas are recorded [NCCO, 2003].

Of total land area of the country 12% is under cultivation (arable land, orchards and vineyards). 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 every year. Wheat, barley, rice and maize are the country's major cereal crops. Self-sufficiency in wheat production was achieved in 2004. In 2007 Iran exported nearly 600,000 tons of wheat while producing 15 million tons. However, it is reported that Iran will purchase 6 million tons of wheat from 15 countries in 2009 because of the drought in 2008 [http://www.pecad.fas.usda.gov/highlights/2008/05/Iran_may2008.htm]. Iran's total rice production stands at 2.2 million tons per year whereas annual consumption is about three million tons (2008). Iran has long been an importer of rice and it imported about 630,000 tons of rice in 2008.

Historically, Iran was self-sufficient in terms of agricultural products until the 1960s. However, in the 1970s it turned to import food from outside of the country. In 1979 the government of Iran set the national goal for self-sufficiency in foodstuffs. Since then commercial farming has replaced subsistence farming. High government subsidies for cereal and other staples and expansion of short-term credit and tax exemptions for farmers were provided to promote self-sufficiency. Currently, the agricultural sector accounts for almost 13% of Iran's GDP, 20% of the employed population, 23% of non-oil exports, 82% of domestically consumed foodstuffs and 90% of raw materials used in the food processing industry [Keshavarz *et al.*, 2005; Stads *et al.*, 2008]. With the increasing water scarcity in many areas and the ever-growing population in the country, the agricultural sector has been facing unprecedented challenges [Faramarzi, *et al.*, 2010].

5.2.2 Multi criteria analysis framework

5.2.2.1 Construction of goal function

Use of a multi criteria approach to adjust the structure of cropping pattern (ASCP) facilitated accounting of the country's diverse agro-climatic, social, and economic conditions. We developed a mixed-integer, multi-objective, linear optimization model

and solved it by linear programming (LP). Figure 5.1 illustrates the framework of the ASCP developed in this study. We used the data of 1990-2004 in the LP procedure as the baseline to allow comparison of various scenarios. In this LP procedure, we focused on the constraints concerning water, land, and wheat self-sufficiency. We considered the inclusion of social, economic and environmental constraints in the LP procedure. However, we found that the model becomes too complicated and no solution could be found. The current LP procedure did not include socio-economic and environmental constraints explicitly, although some of them are partially reflected by the constraints for water, land and national food production. An explicit consideration of social, economic and environmental constraints in determining optimal ASCP will be conducted outside of the LP procedure by assessing the LP results against some of the key factors concerning social equity, economic viability and environmental sustainability [Wiek and Binder, 2005].

Figure 5.2 summarizes construction of the LP stating the objective function as

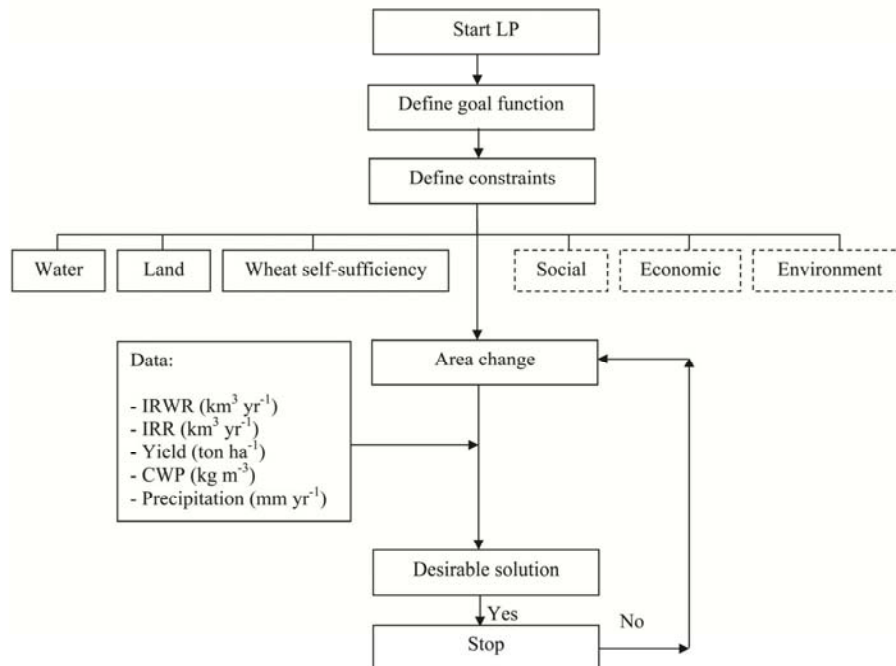


Figure 5.1 - Multi criteria decision analysis framework of the ASCP corresponding to the VWT strategy. IRWR: internal renewable blue water resources, IRR: irrigation water requirement, CWP: crop water productivity. Dash lines in the constraint are the factors that were not considered in this study.

| | | |
|--------------------------------|--|------|
| Objective fn: Maximize | $g = w_1 f_1 + w_2 f_2$ | (1) |
| where: | $f_1 = \frac{1}{15} \sum_{i=1}^{28} \sum_{j=1}^{15} \sum_{k=1}^4 (a_{i,j,k} \times y_{i,j,k})$ | (2) |
| and | $f_2 = \sum_{i=1}^{28} \sum_{j=1}^{15} \sum_{k=1}^4 (\text{delta}_{i,j,k} \times a_{i,j,k})$ | (3) |
| where: | $\text{delta}_{i,j,k} = ((CWP_{i,j,k} \times y_{i,j,k}) - I_k) \times 10^3$ | (4) |
| | $CWP = \frac{y}{ET}$ | (5) |
| | $I_k = \frac{1}{15} \sum_{i=1}^{28} \sum_{j=1}^{15} (CWP_{i,j} \times y_{i,j})$ | (6) |
| Constraints: | | |
| <i>Area:</i> | $A_i = \frac{1}{15} \sum_{k=1}^4 a_{i,j,k} \leq A_{h_max_i}$ | (7) |
| where: | $par_{min_k} \times a_{h_max_{i,k}} \times Z_j \leq a_{i,j,k} \leq par_{max_k} \times a_{h_max_{i,k}}$ | (8) |
| and: | $Z_j = \begin{cases} 0 & \text{if } j \text{ drought year} \\ 1 & \text{if } j \text{ non-drought year} \end{cases}$ | (9) |
| where: | drought year if $pcp_{i,j} < \left(\frac{1}{n} \sum_{j=1}^{15} pcp_j \right)_i$ | |
| <i>Water scarcity:</i> | $WSR_{i,j} = \frac{1}{IRWR_{i,j}} \left[\sum_{k=1}^4 IRR_k + \sum_{r=1}^{16} IRR_r \right]_{i,j} \leq$ $WSR_{h,i} \times Z_j + scar_tol \times (1 - Z_j)$ | (10) |
| where: | $IRR_k = 10^{-8} \times a_k \times \frac{ET_k}{WUE_k}$ | (11) |
| and: | $\left[\frac{1}{15} \sum_{j=1}^{15} WSR_j \right]_i \leq WSR_{h,i}$ | (12) |
| <i>Wheat self-sufficiency:</i> | $P_j = \frac{1}{15} \sum_{i=1}^{28} \sum_{j=1}^{15} p_{i,j} \geq par_{self_suff} \times P_{2004_j}$ | (13) |
| where: | $P_{2004_j} = \frac{pop_j}{pop_{2004}} P_{2004}$ | (14) |

Figure 5.2 - Construction of the LP model for adjustment of the structure of cropping system.

Figure 5.2.

| Definition of terms | | |
|---------------------|----------------------------------|--|
| f_1 | ton | historic average cereal production in the country |
| f_2 | | gain due to adjustment in the structure of cropping pattern (ASCP) |
| w_1, w_2 | - | weights of f_1 and f_2 , respectively |
| a | ha | area |
| y | ton ha ⁻¹ | yield |
| k | - | crop counter (maximum 4) |
| j | - | year counter (maximum 15) |
| i | - | province counter (maximum 28) |
| CWP | ton m ⁻³ | crop water productivity (y/ET) |
| ET | m ³ ha ⁻¹ | evapotranspiration |
| I | ton ² m ⁻³ | historical (1990-2004) national average value of the ($CWP \times y$) |
| A_i | ha | historical area under cultivation of four cereal crops for province i |
| A_{h_max} | ha | historical maximum area under four cereal crops in province i |
| a_{h_max} | ha | historical maximum area of cereal k and province i |
| par_{min} | - | lower percentage of the area change |
| par_{max} | - | upper percentage of the area change |
| Z_j | - | binary variable determining the status of a year as drought (0) or not (1) |
| $WSR_{i,j}$ | - | water scarcity ratio of province i in year j |
| WSR_h | - | historic (average 1990-2004) water scarcity ratio of province i |
| tol_scar | - | tolerable water scarcity ratio |
| IRR_k | km ³ | water used to irrigate crop k |
| $IRWR_{i,j}$ | km ³ | total internal renewable water resources of province i in year j |
| ET_k | mm | consumptive blue water use of crop k |
| WUE | - | water use efficiency (ratio of water used by crop to total water supply) |
| P | ton | adjusted national wheat production averaged over (1990-2004) period |
| P_{2004} | ton | national wheat production in 2004 where zero import is reported |
| $p_{i,j}$ | ton | wheat production for province i and year j |
| par_{self_suff} | - | percentage of self sufficiency |
| pop | - | population |
| pcp | mm | annual precipitation |

well as the constraints. As mentioned earlier in the paper, increasing cereal production and achieving wheat self-sufficiency are of vital national interests of Iran. In view of this situation, maximizing the quantity of cereal crops at the national level is used as the main objective in the multi criteria analysis. Hence, the objective function (Eq. 1) was

formulated as the weighted sum of the average of 1990-2004 cereal production in the country, f_1 , plus an adjustment factor resulting from the changes in the cropping pattern, f_2 . The weights were chosen so as to equalize the effect of each component on the objective function. To maximize the objective function, the areas under cultivation of cereal crops (barley, maize, rice and wheat) were varied across provinces to meet the constraints presented later in this section. As climate of Iran is quite variable across provinces, there are large differences in the performances of different crops in different parts of the country [Faramarzi *et al.*, 2010]. This performance is usually measured by the quantity of the crop water productivity (CWP). This is defined as the amount of crop yield that can be produced by a given amount of water consumptively used in ET (Eq. 5). Hence, the provinces with a better performance in the production of a given crop should gain more area for that crop than the provinces with poorer performance. As a large CWP could also be achieved with small yield and small ET , we multiplied CWP with yield to give more weight to regions with larger yield. This is meaningful in reality as achieving a certain level of food production is vitally important for the country. To determine the relative performance of individual provinces, we constructed the *delta* indicator as shown in (Eq. 4). The index I is the long term (1990-2004) average value of the ($CWP \times y$) at the national level. The I value of barley, maize, rice and wheat were calculated to be 1.348, 6.126, 1.202, and 1.551 ($\text{ton kg m}^{-3} \text{ ha}^{-1}$), respectively. The *delta* factor, therefore, is an important indicator of the marginal gain due to ASCP; for this reason it was added to the objective function to quantify the impact of the change in cropping pattern.

5.2.2.2 Setting up the constraints

Based on historical trend of agricultural area (1990-2004) and personal interviews with agricultural experts we concluded that all agricultural areas in most of the provinces are being potentially used and can not be expanded. Even if there were potentials for expansion, these would be mostly in marginal lands located in ecologically fragile areas. With this consideration, we constrained the total area under cultivation of cereal crops to not exceed historic maximums as expressed in (Eq. 7).

It should be pointed out that in most part of Iran the cereal crops are grown with a crop-fallow sequence or in rotation with chickpea or fodder legume crops [Nasiri, *et al.*, 2008; Filizadeh, *et al.*, 2007]. Therefore the summer cereals (maize and rice) are generally not in rotation with winter cereals (wheat and barley). The total area under

cultivation was calculated as the aggregated area of the four cereal crops considered ($A_{h-\max,i}$ in Eq. 7).

In practice, it is not realistic to assume that if a province has small value of δ for a given crop, this province should give up all the production for that crop. Likewise, if a province has a high value of δ , it is not realistic to assume that all the cereal land should go for this crop. Hence, the constraint in (Eq. 8) was imposed. This constraint ensures that the area change (new area assigned to a crop in a province) is smaller than the historic maximum for that province and larger than minimum while taking the drought years into account through the Z binary operator. Only in drought years minimum area could be set to zero.

Next, we added a water scarcity constraint. Water scarcity ratio (WSR) is defined as the fraction of the total (blue) water use to the total available (blue) water resources [Alcamo et al., 2007]. The constraint in (Eq. 10) is set up in such a way that WSR in each province and in each year does not exceed the historical value except in drought years. In other words, there are some dry years in which WSR can equal a user-defined level of scarcity tolerance expressed as $scar_tol$ in (Eq. 10). In all, irrigation water use of 20 crops were accounted for. Our study focuses on the four cereal crops and their irrigation water uses were calculated based on the adjusted area of cultivation; hence, they are expressed separately in (Eq. 10). For the other 16 crops we used total reported values for every year and province (IRR_r). In this study, we did not consider the possible adjustment of structure of these 16 crops because they are either cash crops and/or non-staple crops with less importance for food security. Lacking information on production costs and benefits as well as the complexity of the cropping systems in cash crops across regions deterred our attempt to implement ASCP for these crops in the optimization procedure. To calculate the irrigation water use of the four cereal crops (IRR_k), we used the consumptive irrigation water use of the crop (ET_k), or blue water consumptive use, which is the SWAT output taken from a previous study [Faramarzi et al., 2010], and adjusted it for the water use efficiency (WUE) obtained from Dehghani, et al., [1999] for each province as expressed in (Eq. 11). A further water resources constraint was added (Eq. 12) to ensure that in the adjusted cropping structure the long term average water scarcity of a province does not exceed its historic value. In the LP procedure, only irrigated crops and areas were considered. We did not include dryland crops because our focus was on

alleviating blue water scarcity. In essence, we assumed a constant structure of dryland crops.

Finally, as wheat is the national strategic crop and self-sufficiency on the production of wheat is the major stakeholder interest, we added the constraint in (Eq. 13) to allow wheat production to take place at different self-sufficiency levels through par_{self_suff} parameter. The self-sufficiency is measured with respect to the production level of the year 2004 (P_{2004}) where no import was reported.

With the above framework, the model is optimized through 10 parameters: par_{min_k} and par_{max_k} for four cereal crops, as well as par_{self_suff} and $scar_tol$.

5.2.2.3 Data compilation and scenario development

Table 5.1 gives detail information on the data type, source of data, spatial and temporal resolution of the available data, and the time period used in the study. The internal renewable blue water resource (*IRWR*) is defined as the sum of stream flow and deep aquifer recharge. The *IRWR* data was modeled at the subbasin spatial and monthly temporal resolution in our previous study, where an extensive calibration validation and uncertainty analyses of the SWAT model of Iran were conducted [*Faramarzi et al.*, 2009, 2010].

The previously developed hydrological model of Iran was re-calibrated and validated for irrigated rice, barley, and maize yield for the period of 1990 to 2004 with a similar procedure as described in *Faramarzi, et al.* [2010] for wheat. The outputs of the subbasin-based model were aggregated to provincial level and were used as an input to the multi-criteria analysis model developed in this study for investigating potential crop pattern change in Iran.

Five scenarios were examined using the data of 1990-2004 as a base to assess water and food situation in Iran. These scenarios are described in Table 5.2 and further discussed in the next section.

5.3 Results and discussion

5.3.1. ASCP under different scenarios and its national impact

The optimum parameter values for each scenario are given in Table 5.3. Depending on the scenarios, we obtained different parameter values. In S1, we initially set the wheat production to the self-sufficiency level but then relaxed this constraint as

Table 5.1 - List of the data used in this study.

| Data group | Data availability (criteria) | Data source | Spatial/temporal resolution | Time series |
|-------------|--|---|-----------------------------------|-------------------|
| Hydrology | Volume of blue water resources availability, <i>IRWR</i> ($\text{km}^3 \text{ yr}^{-1}$) | SWAT prediction [Faramarzi, et al., 2009] | Sub-basin, monthly | 1990-2004 |
| Climate | Precipitation (mm) | [Faramarzi, et al., 2009] | Sub-basin, daily | 1990-2004 |
| Agriculture | Crop yield (ton ha^{-1}) | MOJA and SWAT prediction [Faramarzi, et al., 2010] | Crop specific, provincial, annual | 1990-2004 |
| | Cereal crop water productivity (<i>CWP</i>) (kg m^{-3}) | SWAT prediction [Faramarzi, et al., 2010] | Crop specific, provincial, annual | 1990-2004 |
| | Crop water consumption, <i>ET</i> (mm yr^{-1}) | [Farshi et al., 1997] and SWAT prediction [Faramarzi, et al., 2010] | Crop specific, provincial | Long-term average |
| | Historical water use efficiency | [Dehghani, et al., 1999] | Provincial specific | Long-term average |
| Population | Area under cultivation of crop (ha) | MOJA ^a | Province, annual | 1990-2004 |
| | -- | SCI ^b | Provincial | 1990-2004 |
| | -- | SCI | National | 1990-2004 |

^a MOJA: Ministry of Jihad-e-Agriculture.

^b SCI: Statistic Center of Iran.

Table 5.2 - Description of the 5 scenarios modelled in this study.

| Scenarios | Conditions | Description |
|-----------|--|---|
| S1 | Constraints as described in the LP of Table 1 | Continuing the historic trend with constraints limited by historical values |
| S2 | <i>WSR</i> in 10 water abundant provinces allowed to be higher than historic values, up to a maximum of 0.7 (leaving 30% for environmental flow [Yuan et al., 2009]) | Continuing the historic trend while giving flexibility to water use in water abundant provinces for food production |
| S3 | Restrictions on <i>WSR</i> were relaxed in all provinces to produce maximum cereal and wheat at self sufficiency level | This scenario is in favour of food security. The practice will of course not be sustainable |
| S4 | Cereal crops were not grown in seven water-scarce provinces where <i>WSR</i> >1, and maximized in others, while limiting <i>WSR</i> to 1 | This scenario is in favour of water security. |
| S5 | <i>WUE</i> in (Eq. 11) was raised to 70% in all provinces instead of its historic value of (15%-36%) | Improved irrigation networks and water conveyance systems is one of the proposed approaches to improve water use efficiency in Iran [NRC, 2005] |

Table 5.3 - LP model parameters obtained for all scenarios.

| Parameter | S1 | S2 | S3 | S4 | S5 |
|-----------------------------|------|------|-------|------|------|
| $Par_{\min, \text{barley}}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Par_{\max, \text{barley}}$ | 0.92 | 0.92 | 0.99 | 0.93 | 1.00 |
| $Par_{\min, \text{maize}}$ | 0.40 | 0.04 | 0.00 | 0.00 | 0.00 |
| $Par_{\max, \text{maize}}$ | 0.84 | 0.95 | 1.00 | 0.92 | 1.00 |
| $Par_{\min, \text{rice}}$ | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Par_{\max, \text{rice}}$ | 0.96 | 1.00 | 1.00 | 0.99 | 1.00 |
| $Par_{\min, \text{wheat}}$ | 0.31 | 0.46 | 0.15 | 0.00 | 0.60 |
| $Par_{\max, \text{wheat}}$ | 0.98 | 0.96 | 1.00 | 1.00 | 1.00 |
| $Scar_tol$ | 7.70 | 7.70 | 11.90 | 1.94 | 5.60 |
| Par_{self_suff} | 0.89 | 0.92 | 1.00 | 0.57 | 1.00 |

there were no solutions. This indicates that under the current management situation, it is not possible to reach wheat self-sufficiency. Annual trend of wheat production for all scenarios are illustrated in Figure 5.3. In Table 5.4, the quantities of cereal production obtained by solving the ASCP optimization problem are 13.3 and 14.2 million tons yr^{-1} in scenarios S1 and S2, respectively, as compared to the historic average amount of 12.5 million tons yr^{-1} on the irrigated land. The self-sufficiency level based on the per capita production of 2004 was calculated to be 142 kg $\text{capita}^{-1} \text{yr}^{-1}$ for irrigated wheat. The average wheat production in the country during 1990-2004 was 24% smaller than the self-sufficiency level. This was improved to 10% and 8% smaller than the self-sufficiency level in the S1 and S2, respectively. At the same time, the national WSR decreased from 0.73 (historic value) to 0.72 in S1 and increased to 0.75 in S2. The increase of WSR in S2 was due to the increased water use in water-abundant provinces.

In S3, production of all four crops increased in most provinces except barley and maize that partially decreased in some northern and southern areas. Without water constraint, on average wheat could be produced at the self-sufficiency level during 1990-2004. In wet years it was slightly above the self-sufficiency level whereas in dry years it was below (Figure 5.3). However, the high level of cereal production in this scenario could not be sustainable in the long term because the national WSR increased from 0.73 to 0.85 and in many provinces, continuous groundwater over extraction will lead to a total exhaustion of groundwater aquifers in many provinces in arid and semi-arid regions.

In S4, the optimal ASCP strongly depended on the WSR . In this scenario, cereal crops were either eliminated or significantly decreased in most parts of the country. Wheat production could only meet 60% of the self-sufficiency level. The national

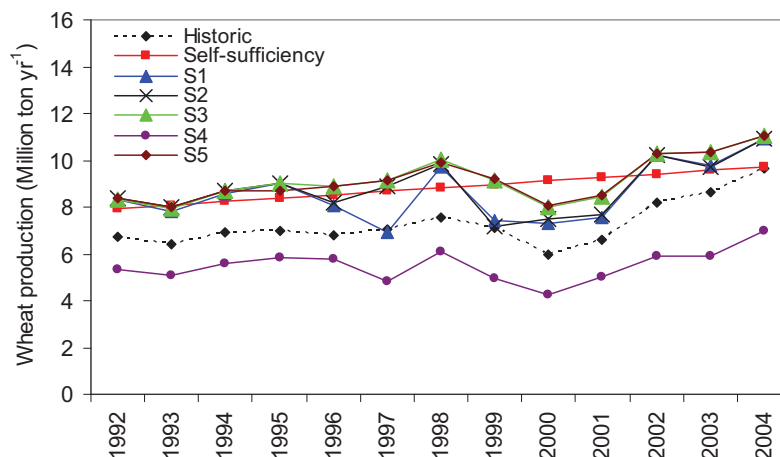


Figure 5.3 - National wheat production trend resulted from different water and food scenarios.

average WSR decreased from 0.73 to 0.58, indicating a significant reduction in the pressure on the country's water resources.

In S5, where all provinces were assumed to increase their irrigation water use efficiency to 70%, wheat and other cereal production were larger than historic levels. Self-sufficiency was also achieved for wheat while *WSR* decreased from 0.73 to 0.53. These results suggest that improving water use efficiency in irrigation can substantially alleviate the water scarcity situation, while supplying more food at the same time.

Table 5.4 - Irrigated cereal production and water scarcity ratio at national level averaged over 1990-2004 for historic and scenario results.

| Scenarios | Production (Million ton yr ⁻¹) | | | | | <i>WSR</i> ^a (km ³ km ⁻³) |
|-----------|--|-------|------|-------|--------|--|
| | Barley | Maize | Rice | Wheat | Cereal | |
| Historic | 1.8 | 1.0 | 2.4 | 7.3 | 12.5 | 0.73 |
| S 1 | 1.4 | 0.9 | 2.4 | 8.6 | 13.3 | 0.72 |
| S 2 | 1.6 | 1.3 | 2.5 | 8.9 | 14.2 | 0.75 |
| S 3 | 2.0 | 1.3 | 2.8 | 9.6 | 15.7 | 0.85 |
| S 4 | 0.7 | 1.1 | 2.5 | 5.5 | 9.8 | 0.58 |
| S5 | 1.9 | 1.3 | 2.7 | 9.6 | 15.6 | 0.53 |

^a *WSR*: water scarcity ratio which is water use divided by renewable water availability.

5.3.2 ASCP under different scenarios and its provincial impact

Figure 5.4 shows the structure of cropping pattern in the period of 1990-2004 across the country. Figures 5.5 to 5.9 show the respective changes under the five scenarios. The coloured circles show the percent deviation in cropping area of various scenarios from the historic average levels. The background colours show the *delta* index,

with positive values indicating better performance ($CWP \times Y$) than the national average and negative values indicating worse performance. Ideally, VWTS dictates that provinces with better performance for a given crop should in general gain more area for that crop than provinces with poorer performance. Figure 5.5 and 5.6 show this trend for all cereals except wheat. In general, barley, rice, and maize show a decrease in provinces with negative δ and increase in provinces with positive δ . As wheat self-sufficiency is an additional driving force in the LP model, its area was increased in all provinces. In S1, rice is removed or largely decreased in most of the provinces where CWP is small except some northern provinces where CWP of rice is large. For example, we may compare the arid central province of Esfahan with the water abundant northern province of Gilan. The former has the long-term average annual (1990-2004) yield and CWP of 6.1 ton ha^{-1} and 0.31 kg m^{-3} respectively, resulting in a performance value of 1.891. The latter has the average yield and CWP of 3.9 ton ha^{-1} and 0.57 kg m^{-3} , respectively, resulting in a performance value of 2.222. Considering the national I value for rice ($1.202 \text{ ton kg m}^{-3} \text{ ha}^{-1}$), both provinces have high performance with a positive δ value. As water scarcity (represented by WSR) is a limiting factor in Esfahan province, the LP model sought to reduce the rice production area in Esfahan despite its high performance. A reduction in rice cultivation area in the central and southern provinces will alleviate water scarcity, since the evaporative demand in these areas is extremely high and large amounts of water are required for paddy cultivation.

Relaxing WSR in some water abundant provinces (as defined in S2), led to slightly different adjustment in the structure of cropping pattern (Figure 5.6). Rice cultivation was increased in water-abundant provinces. Maize was expanded in most parts of the country with high maize production performance. The area of barley cultivation was slightly increased in some provinces.

In Figures 5.5 to 5.9, the total area allocated to cereal crop production was increased in ASCP scenarios in some provinces (e.g. Fars located in the south, S2). This does not contradict to the land availability constraint in the LP model. In the model the total area that can be devoted to cereals in a given province was limited to the long-term maximum land under cereal crops (Eq. 7, Eq. 8). In Figures 5.5 to 5.9, the deviation from “historical average” is shown instead of the “historical maximum”.

S3 results in Figure 5.7 show that wheat areas increase in all provinces, resulting from the removal of restrictions on WSR to allow maximum wheat production. The area

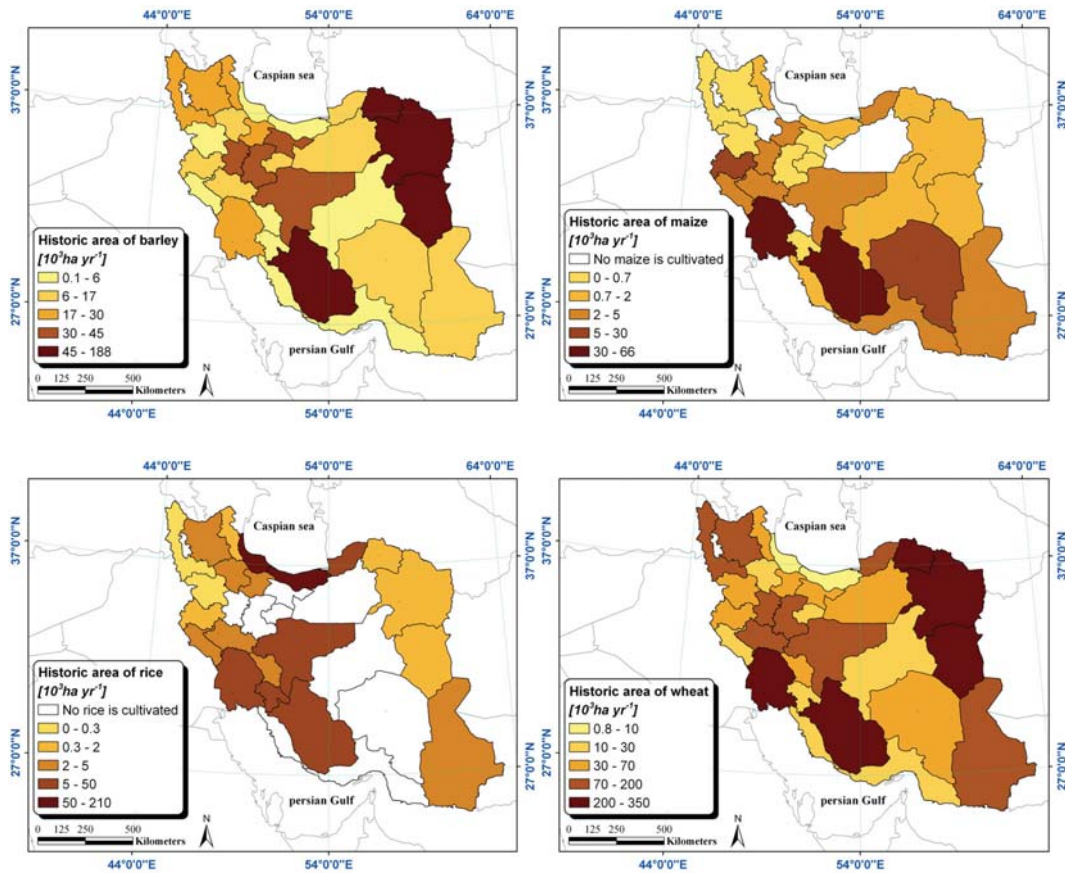


Figure 5.4 – Long-term (1990-2004) average area under cultivation of cereal crops which is historically practiced at different provinces.

changes of the other cereals are again mostly consistent with VWTS.

In S4, where water sustainability is given a higher priority, the cereal crop areas are decreased in the eastern part of the country, where water scarcity is severe, while wheat production is increased in the western part of the country where water scarcity is not critical (Figure 5.8). Rice and maize production are highly consistent with VWTS, and barley is decreased in most of the provinces.

In S5, water scarcity was found to be less of a limiting factor than in S1 and S2 due to the assumed improvement in the irrigation efficiency. Therefore, the LP model sought to maximize cereal production and to meet wheat at the self-sufficiency level while using less water than S1 and S2. We found a rather similar cropping pattern as S3 in this scenario but with less *WSR* in individual provinces as well as at the national level (Figure 5.9).

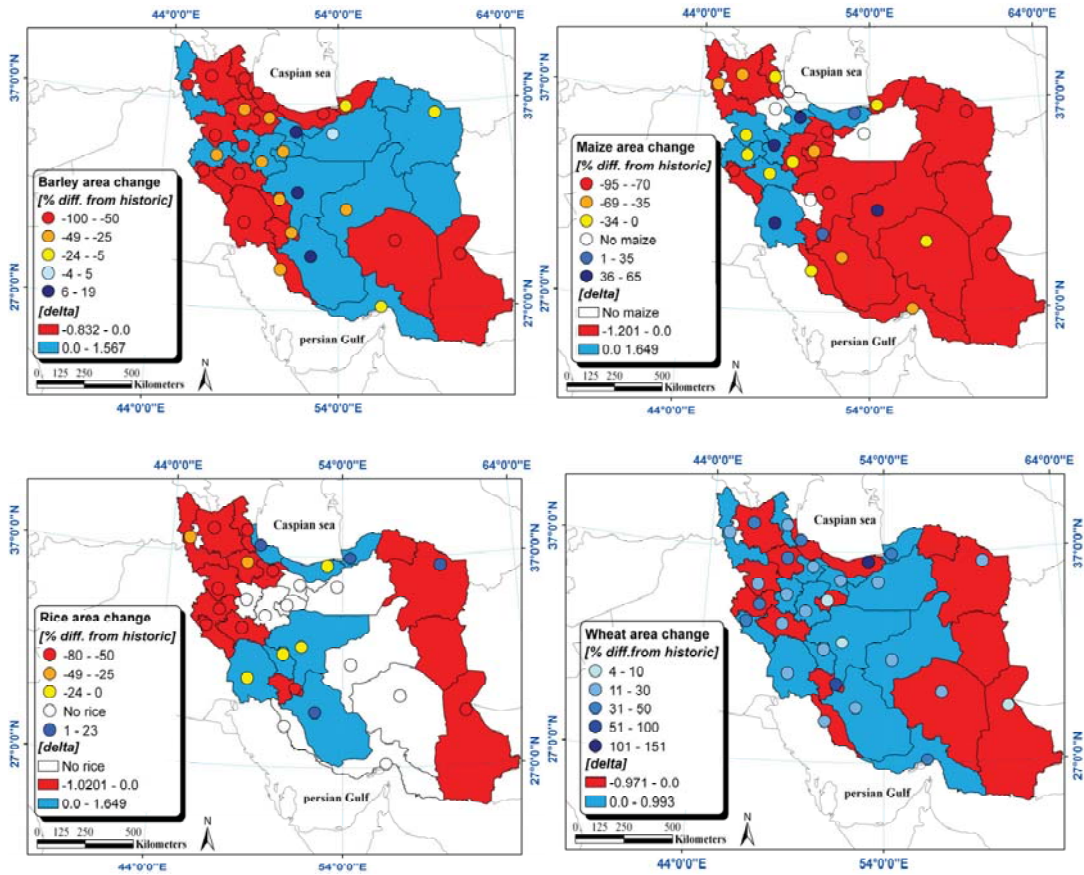


Figure 5.5 – Adjusted structure of cropping pattern in S1. Circles show % differences from the long-term (1990-2004) average area in Figure 5.4. The background colors show the provinces' delta index where blue indicates positive performance and red indicates negative performance with respect to national average.

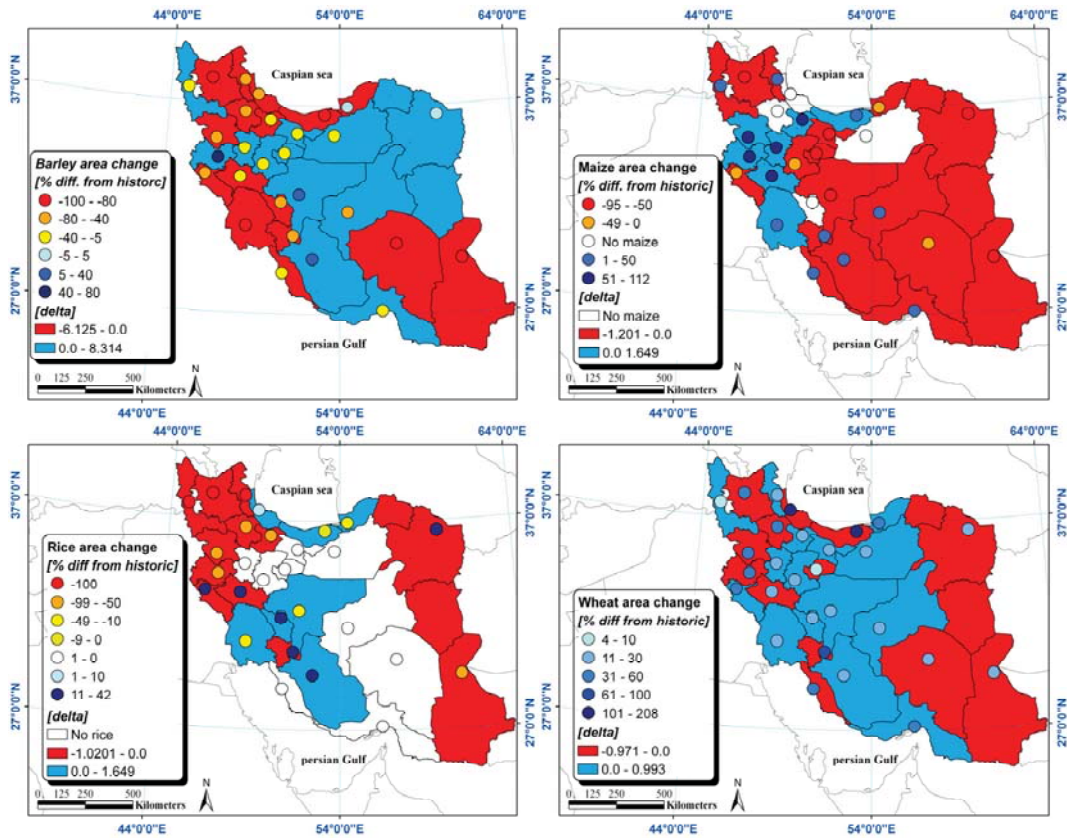


Figure 5.6 – Adjusted structure of cropping pattern in S2. Circles show % differences from the long-term (1990-2004) average area in Figure 5.4. The background colors show the provinces' delta index where blue indicates positive performance and red indicates negative performance with respect to national average.

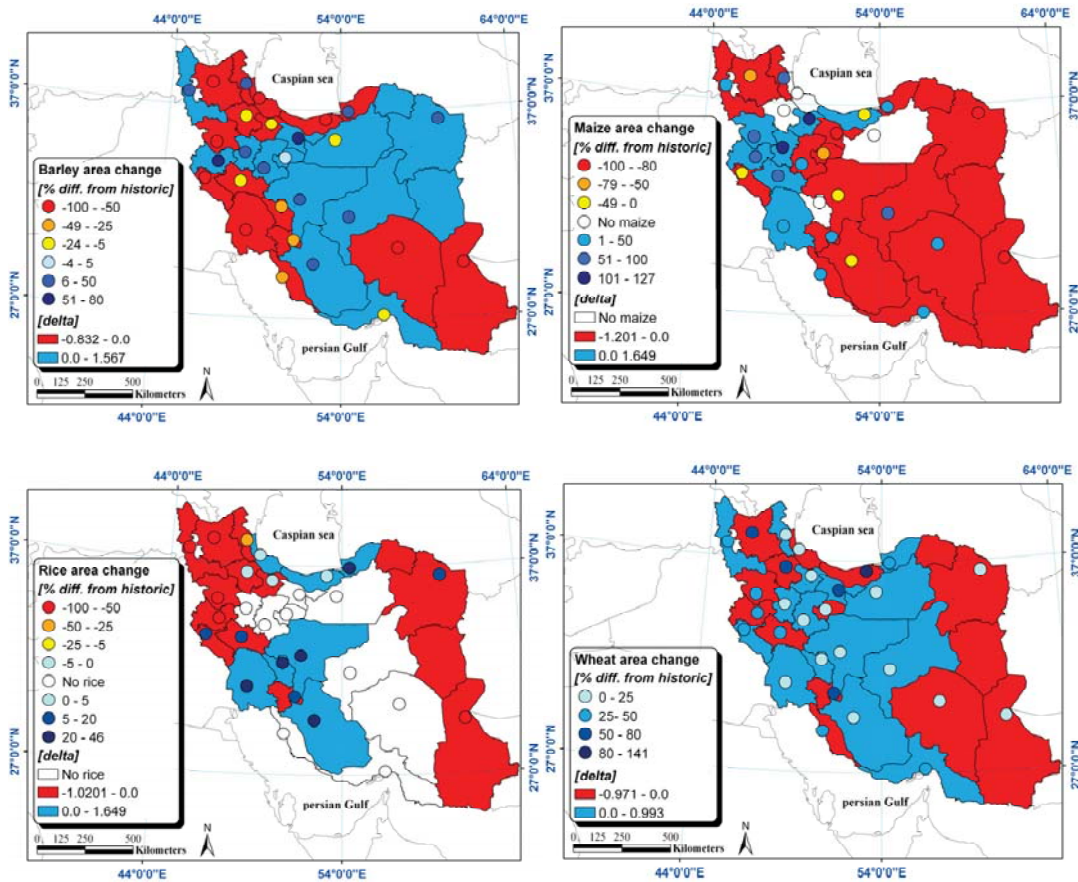


Figure 5.7 – Adjusted structure of cropping pattern in S3. Circles show % differences from the long-term (1990-2004) average area in Figure 5.4. The background colors show the provinces' delta index where blue indicates positive performance and red indicates negative performance with respect to national average.

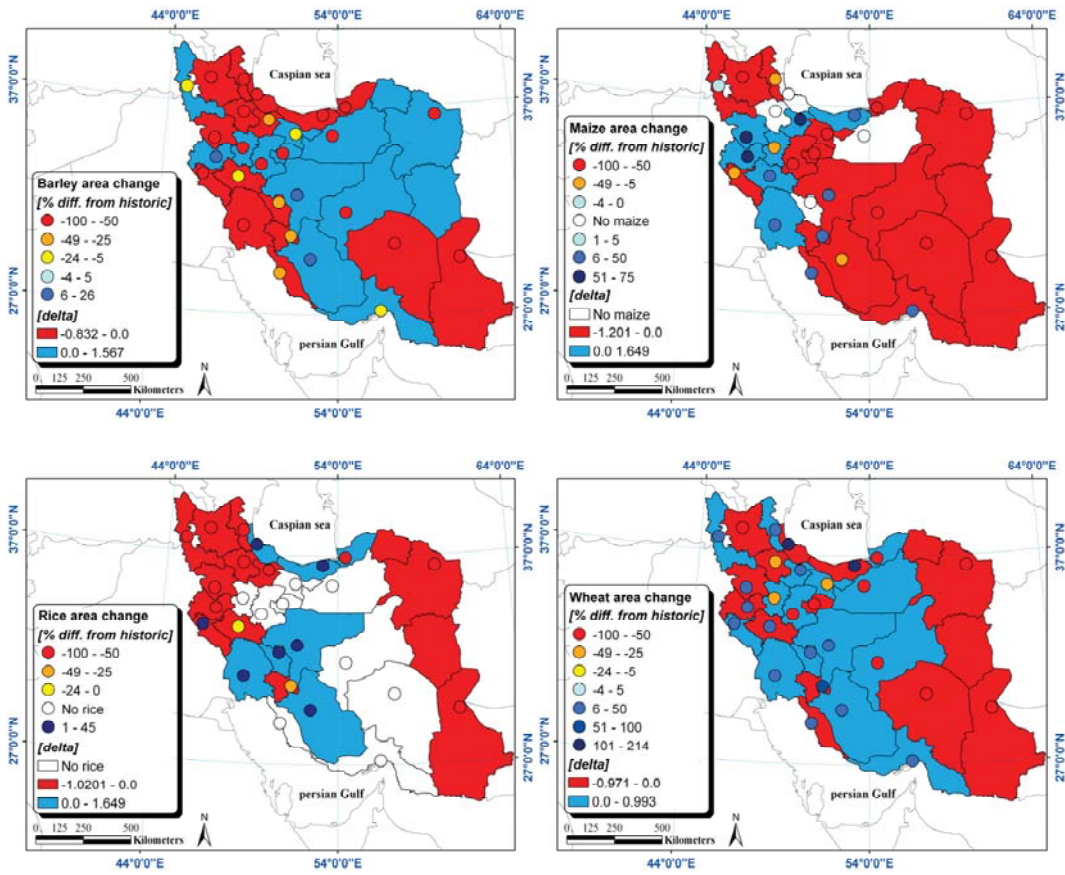


Figure 5.8 – Adjusted structure of cropping pattern in S4. Circles show % differences from the long-term (1990-2004) average area in Figure 5.4. The background colors show the provinces' delta index where blue indicates positive performance and red indicates negative performance with respect to national average.

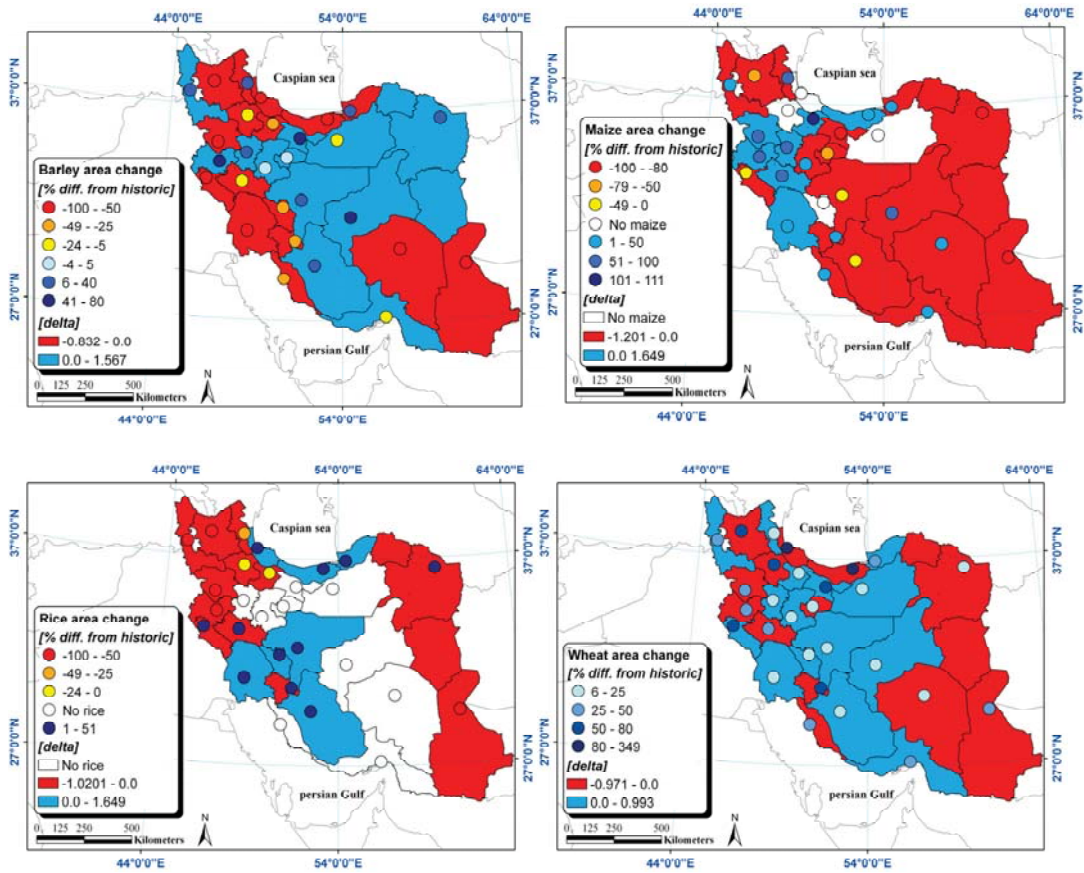


Figure 5.9 – Adjusted structure of cropping pattern in S5. Circles show % differences from the long-term (1990-2004) average area in Figure 5.4. The background colors show the provinces' delta index where blue indicates positive performance and red indicates negative performance with respect to national average.

5.3.3. Impact of ASCP on WSR in different provinces

Figure 5.10 shows how the optimized ASCP scenarios would change blue water use relative to the current internal renewable blue water resources (*IRWR*). In S1 and S2, most of the wet regions in the west and north of the country, and also some provinces in the south would use up to 12% more of their blue water resources, while water use in the eastern and central dry provinces would slightly decrease with respect to their blue water resources (*IRWR*). A reduction in water use by more than 100% in some provinces implies lesser use of deep fossil groundwater and/or other external sources.

S3 would lead to increase in water use by up to 200% of renewable blue water resources in some northern provinces and 0-50% in the dry central and eastern regions. Increasing the water use in regions where water scarcity is already severe will not be sustainable and agricultural production will eventually decrease due to the lack of water and soil erosion such as salinity. Ghom is the only province for which a decrease of water use is predicted in this scenario. As the *IRWR* of Ghom province is meager, a decrease of 128% in water use will not drastically improve the situation. This scenario shows that under the current practice, achieving long term wheat self-sufficiency is impossible.

In S4, the eastern half of the country and most of the north-western provinces will decrease water use by up to 600% of their respective *IRWR*. In many parts of Iran, water supply solely depends on groundwater. During the past two decades, overexploitation of groundwater has caused a water table drawdown in most of the 600 aquifers in Iran [Motagh *et al.*, 2008]. Akhavan *et al.* [2009] reported a 50 m drawdown in the province of Hamedan in western Iran in the past 30 years. Reducing water use is absolutely necessary to halt the groundwater drawdown.

In S5, water use is decreased by 25% of *IRWR* in the central part of the country and up to 100% in the eastern region. Khorasan province located in the north east of Iran is one of the major wheat producers in the country and has a large area under wheat cultivation. Reduction in the water use by up to 100% of the *IRWR* in this province would have a significant impact on the conservation of water resources in the region and consequently on the availability of water for wheat production in the long run.

5.4 Implications of ASCP

5.4.1 Implications of ASCP scenario results for interregional VWT

We used the provincial data to study the possible inter-provincial trade under

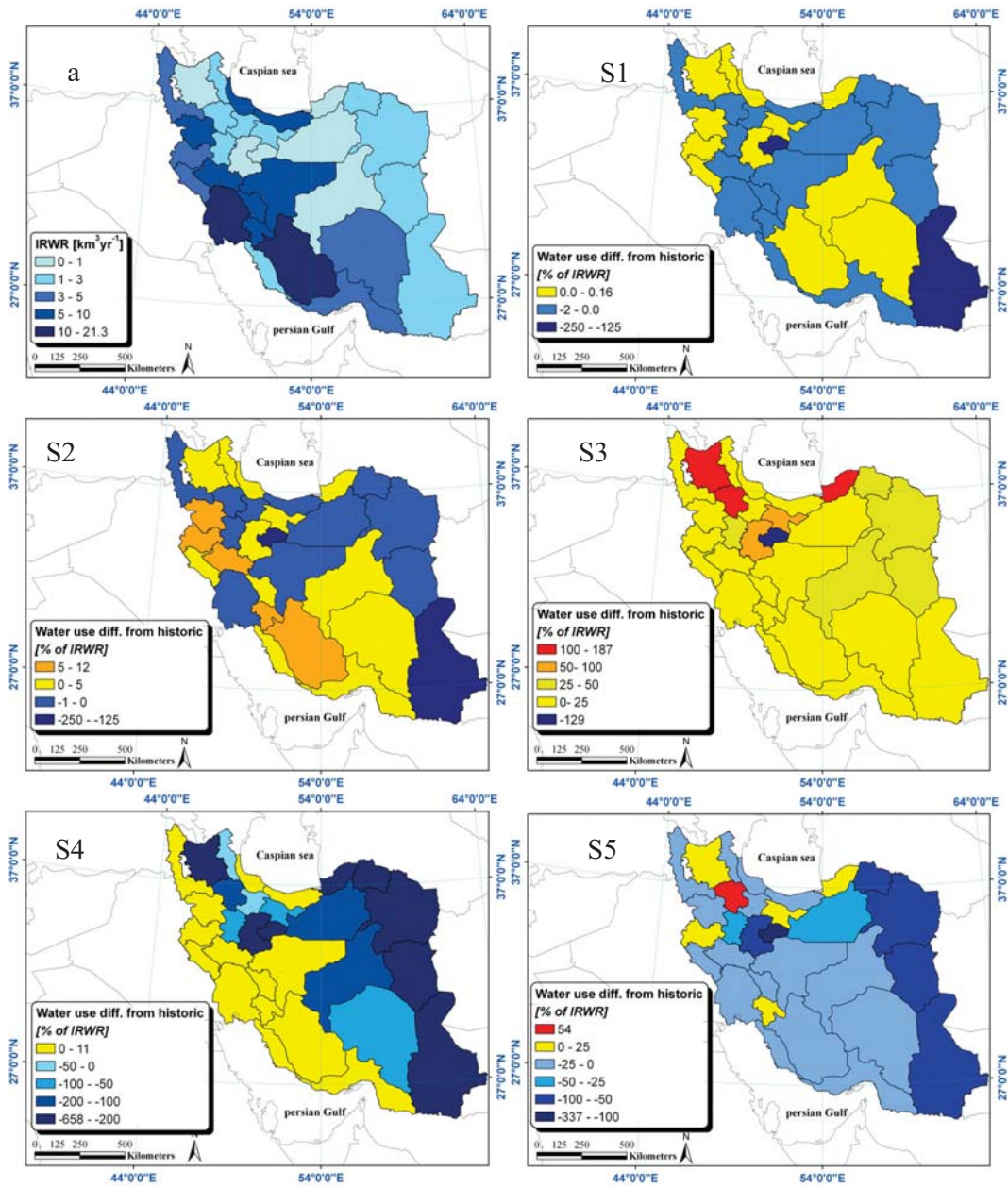


Figure 5.10 - Map of the differences in water use as percentage of internal renewable water resources resulting from adjustment in the structure of cropping pattern. Figure 5.10a shows the historic distribution of the internal renewable blue water resources (IRWR). The blue areas show a decrease in water use.

different ASCP scenarios. Using the provincial population data of 1990–2004 and the wheat self-sufficiency benchmark of $142 \text{ kg capita}^{-1} \text{ year}^{-1}$, we calculated the annual provincial wheat requirement to meet self-sufficiency level. Furthermore, we calculated deviation of the scenario results from the self-sufficiency level to estimate wheat surplus or deficit in individual provinces. Moreover, we divided the obtained wheat

surplus/deficit values by the *CWP* (kg m^{-3}) of wheat in different provinces to obtain virtual water content. In doing so, we calculated the amount of virtual water in the form of wheat trade between surplus and deficit provinces. Figure 5.11 illustrated the average of these values over 1990-2004 period in different provinces. In all scenarios, we found a large amount of tradable virtual water due to wheat surplus in the provinces of Fars, Khozestan, Khorasan, Golestan, Hamedan, Lorestan, Ghazvin, and Markazi. This virtual water can be exported to provinces with wheat deficit, where large amounts of water would otherwise be needed to produce the same quantity of wheat (shown as red bands). Aggregating these values on the national scale, we found that wheat export from wheat surplus provinces would compensate 89% of wheat deficit in the S1 scenario, 92% in S2, 100% in S3, 31% in S4 and 100% in S5. In total, wheat-deficit provinces would receive 5.5 billion m^3 of virtual water by importing wheat in the S1 scenario, 5.1 billion m^3 in S2, 5.4 billion m^3 in S3, 3.5 billion m^3 in S4 and 5.4 billion m^3 in S5. A similar analysis of the VWT potentials for other cereal crops shows that the intra-country VWT is a valid option to balance water resources between water-abundant and water-scarce provinces. This would be a promising strategy for the country from the point of view of sustainable use of water resources. The reduction of cereal production in importing provinces, however, is also likely to result in lesser income in these provinces. But the water saved, in otherwise used inefficiently for production, could be used in more high-valued production in greenhouses and hydroponics, or in more profitable industries. After all, producing highly subsidized, low-value, and high water-intensive food crops through over-exploitation of water resources could not lead to sustainable food production in the long-run.

5.4.2 Implications of ASCP scenarios for water transfer projects in Iran

ASCP and inter-regional VWT could be an alternative for water transfer projects, which are usually costly and environmentally unfriendly and destructive. Table 5.5 shows the volume of water which is transferred from source to recipient basins through 17 major water transfer projects for agricultural purposes in Iran. As the irrigated agriculture is the largest water user (more than 90%) and wheat is the dominant crop in terms of sown area and water requirement, we assumed that 90% of the water transfer in the multi-purpose projects (A,M,I and A,M, in Table 5.5) and 100% of the water in A-purpose projects are diverted to irrigate wheat. Ignoring the possible water loss due to transfer from source to recipient basin, we used the volume of water transferred to

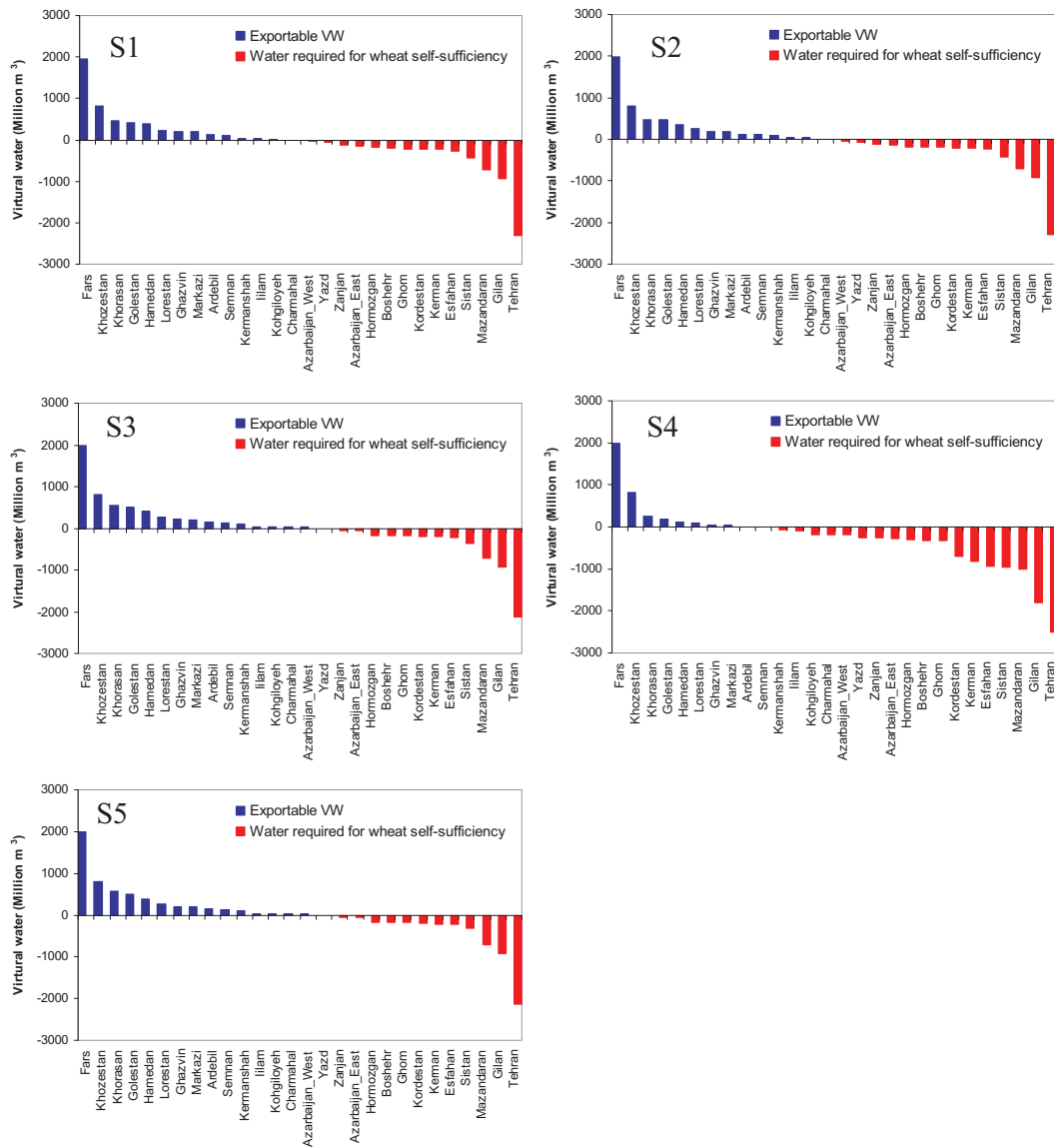


Figure 5.11 - long-term (1990-2004) average virtual water exported through wheat trade in provinces where excess wheat is produced (blue) and the amount of water required to produce wheat in the importing provinces (red).

calculate the amount of wheat which could be produced in the recipient basin. We then calculated the volume of water use if that much of wheat would be produce in the source basin. Figure 5.12 compares the volumes of water use in the recipient basin and in the source basin for the given amount of wheat produced in the two basins. It is seen that out of 17 water transfer projects only six of them show a higher water use in the source basin to produce a given amount of wheat than the recipient basin. In the rest of the projects the volume of water required in recipient basin is larger than the source basin. This implies that the water is transferred from the areas with higher *CWP* to the areas with lower

Table 5.5 - Major inter-basin water transfer projects in Iran.

| Project | Source basin | Source river | Recipient basin | Province | | Recipient | Purpose ^a | Volume of water transfer (MCM) ^b |
|-------------------|-----------------|-------------------------|-------------------------|-----------------------|------------|-----------|----------------------|---|
| | | | | Source | Province | | | |
| Beheshtabad | Karun | Beheshtabad | Central (Zayandeh Rud) | Chaharmahal Bakhtiary | Esfahan | A, M, I | 1100 | |
| Haraz | Haraz-Ghareh Su | Haraz | Ghareh Su and Gorgan | Mazandaran | Golestan | A, M, I | 890 | |
| Sirvan | West | Sirvan-Azad Rud | Karkheh | Kordestan | Kermanshah | A | 700 | |
| Dasht Abbas | Karkheh | Karkheh | West Border | Kozerstan | Ililam | A | 500 | |
| Chamshir | Jarahi-Zoherth | Zohreh | Haleh Rud | Fars | Bushehr | A | 500 | |
| Taleghan | Caspian Sea | Taleghan | Central (Salt Lake) | Tehran | Tehran | A, M | 420 | |
| Marbar | Karun | Marbar | Central (Sirjan River) | Esfahan | Fars | A, M, I | 320 | |
| Kuhrang-1 | Karun | Kuhrang | Central (Zayandeh Rud) | Chaharmahal Bakhtiary | Esfahan | A, M, I | 297 | |
| Chaloos | Caspian Sea | | | Gilan | Mazandaran | A | 280 | |
| Kuhrang-3 | Karun | Kuhrang | Central (Gavkhui Swamp) | Chaharmahal Bakhtiary | Esfahan | A, M, I | 268 | |
| Gavshan | West | Sirvan | Karkheh | Kordestan | Kordestan | A, M, I | 250 | |
| Kuhrang-2 | Karun | Kuhrang | Central (Zayandeh Rud) | Chaharmahal Bakhtiary | Esfahan | A, M, I | 246 | |
| Gukan | Karun | Gukan | Central | Esfahan | Esfahan | A, M, I | 220 | |
| Solekan-Rafsanjan | Karun | Solekan | Central | Chaharmahal Bakhtiary | Kerman | A | 200 | |
| Cheshmeh Langan | Karun | Sibak-Sardab-Ch. Langan | Central (Gavkhui Swamp) | Esfahan | Esfahan | A, M, I | 120 | |
| Khadangestan | Karun | Cheshmeh Langan | Central (Gavkhui Swamp) | Esfahan | Esfahan | A, M, I | 100 | |
| Soleymanshah | West | Gaveh Rud | Karkheh | Kermanshah | Kermanshah | A, M | 40 | |

^a A: agriculture, M: municipal, I: industry.

^b MCM: million cubic meter per year.

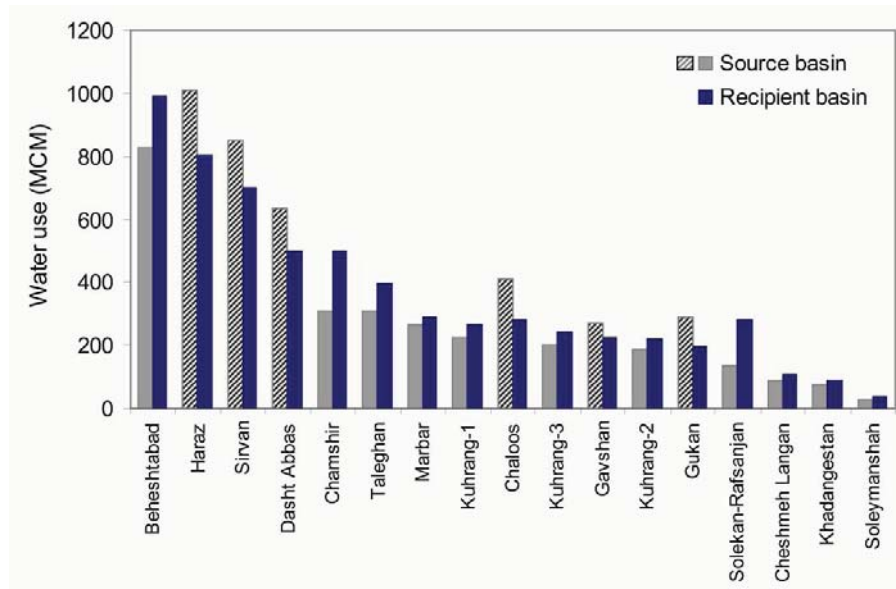


Figure 5.12 - Comparison of the real water transfer and virtual water that could be transferred via wheat export to the recipient basins of major water transfer projects in Iran.

CWP. The results here suggest that most of the water transfer projects in Iran may not be efficient from water resources utilization point of view. We did not address water quality in this paper, but it has been shown that [Afkhani *et al.*, 2007] water withdrawal is one of the direct factors adversely affecting water quality of the Karoun-Dez river systems.

5.5 Limitations of the study and further research

It is important to note that the approaches used in this study do not account for other important factors influencing food trade and decision making of governments and farmers. For instance water quality is an important issue that should be carefully assessed in the analysis of VWTS [Dabrowski *et al.*, 2009]. The environmental impact of agricultural activities in exporting provinces needs more precise assessment in the intra-country VWTS. Other factors such as socio-economy (e.g. social adaptive capacity, unemployment, immigration, social equity, farm income, etc.) and national security considerations [Qadir *et al.*, 2003; Chapagain *et al.*, 2006] are also essential in VWTS studies. In our multi-criteria model, we took water in the centre of ASCP and VWTS analyses and ignored the other factors to avoid complexities and no solution scenarios at this first stage. These factors will be addressed in future studies as we move further in the direction of integrated multi-criteria studies.

Another limitation in this study is the uncertainty analysis that we did not address due to a deterministic nature of the optimization procedure used in this work. Accounting for input data uncertainty would be relevant for providing results with more confidence.

Finally, we assessed in this study the intra-country VWTS potentials to improve water and food security using water resources, agricultural, population, and climate data from 1990 to 2004. The impacts of global climate change on water resources availability [Abbaspour *et al.*, 2009] and on irrigated and rainfed cereal crop yields should also be addressed while assessing the feasibility of intra-country VWTS in any country.

References

- Abbaspour, K. C., M. Faramarzi, S. S. Ghasemi, and H. Yang (2009), Assessing the impact of climate change on water resources in Iran, *Water Resour. Res.*, *45*, W10434, doi:10.1029/2008WR007615.
- Afkhami, M., M. Shariat, N. Zaafarzadeh, H. Ghadiri, and R. Nabizadeh (2007), Regional water quality management for the Karun-Dez river basin, Iran, *Water Environ. J.*, *21*, 192-199, doi:10.1111/j.1747-6593.2007.00070.
- Agha, S.R. (2006), Use of goal programming and integer programming for water quality management – A case study of Gaza Strip, *European Journal of Operational Research*, *174*, 1991-1998, doi:10.1016/j.ejor.2005.06.007.
- Alcamo, J., M. Flörke, and M. Märker (2007), Future long-term changes in global water resources driven by socio-economic and climatic changes, *Hydrolog. Sci. J.*, *52*(2), 247-275, doi: 10.1623/hysj.52.2.247.
- Allan, J.A. (1997), 'Virtual Water': A Long Term Solution for Water Short Middle Eastern Economies?', Occasional Paper, SOAS Water Issues Group, King's College, UK.
- Al-Zahrani, M.A., and A.M. Ahmad (2004), Stochastic goal programming model for optimal blending desalinated water with groundwater, *Water Resources Management*, *18*, 339-352, doi: 10.1023/B:WARM.0000048487.05662.88.
- Akhavan, S. S.F. Mousavi, J. Abedi-Koupai, and K.C. Abbaspour, Conditioning DRASTIC model to simulate nitrate pollution, Case study: Hamadan-Bahar Plain. *Environmental Geology Journal*, in review.

- Ardakanian, R., (2005), Overview of water management in Iran, in *Water conservation, reuse, and recycling*, Proceeding of an Iranian American workshop, pp. 153-172, The National Academies Press: Washington, D.C.
- Chapagain, A.K., A.Y., Hoekstra, H.H.G., Savenije (2006), Water saving through international trade of agricultural products, *Hydrol. Earth Syst. Sci.*, 10, 455–468.
- Dabrowski, J.M., K. Murray, P.J. Ashton, and J.J. Leaner (2009), Agricultural impacts on water quality and implications for virtual water trading decisions, *Ecol. Econ.*, 68, 1074-1082, doi:10.1016/j.ecolecon.2008.07.016.
- Dehghani, S.H., A. Alizadeh, and A. Keshavarz (1999), *Implementation of Water Use Pattern in Terms of Volumetric Supply of Water to Farmers*, Iranian Agricultural Research Institute (IAERI) Press, Tehran, Iran.
- Faramarzi, M., K.C. Abbaspour, R. Schulin, and H. Yang (2009), Modelling blue and green water resources availability in Iran, *Hydrol. Process.*, 23(3), 486-501, doi: 10.1002/hyp.7160.
- Faramarzi, M., H. Yang, R. Schulin, and K.C. Abbaspour, Modeling Wheat Yield and Crop Water Productivity in Iran: Implications of Agricultural Water Management for Wheat Production. *Agr. Water Manage.*, submitted.
- Farshi, A.A., M.R. Shariati, R. JaroLlahi, M.R. Ghaemi, M. Shahabifar, and M.M. Tavallaei (1997), *An Estimate of Water Requirement of Main Field Crops and Orchards in Iran*, 900 pp., Vol. 1, Ministry of Agriculture, Agricultural and Natural Resource Organization, and Water and Soil Research Institute Press, Karaj, Iran.
- Figueria, J., B. Roy (2002), Determining the weights of criteria in the ELECTRE type methods with a revised Simo's procedure, *Eur. J. Oper. Res.*, 139, 317-326, doi:10.1016/S0377-2217(01)00370-8.
- Filizadeh, Y., A. Rezazadeh, and Z. Younessi (2007), Effects of Crop Rotation and Tillage Depth on Weed Competition and Yield of Rice in the Paddy Fields of Northern Iran, *Journal of Agricultural Science and Technology*, 9, 99-105.
- Foued, B.A., and m. Sameh (2001), Application of goal programming in a multi-objective reservoir operation model in Tunisia, *European Journal of Operational Research*, 133, 352-361, doi:10.1016/S0377-2217(00)00303-9.
- Ines, A.V.M., K. Honda, A. Das Gupta, P. Droogers, and R.S. Clemente (2006), Combining remote sensing-simulation modeling and genetic algorithm

- optimization to explore water management options in irrigated agriculture, *Agr. Water Manage.*, 83, 221-232, doi:10.1016/j.agwat.2005.12.006.
- Kangas, A., J. Kangas, and J. Pykalainen (2002), Outranking methods as tools in strategic natural resources planning, *Silva Fennica*, 35, 215–227.
- Keshavarz, A., S. Ashrafi, N. Hydari, M. Pouran, and E. Farzaneh, (2005), Water allocation and pricing in agriculture of Iran, in *Water conservation, reuse, and recycling*, Proceeding of an Iranian American workshop, pp. 153-172, The National Academies Press: Washington, D.C.
- Makowski, D., E.M.T. Hendrix, M.K. van Ittersum, W.A.H. Rossing (2000), A framework to study nearly optimal solutions of linear programming models developed for agricultural land use exploration, *Ecol. Model.*, 131, 65-77, doi:10.1016/S0304-3800(00)00249-0.
- Mau-Crimmins, T., J.E. de Steiguer, and D. Dennis (2005), AHP as a means for improving public participation: a pre–post experiment with university students, *Forest Policy and Economics*, 7, 501– 514, doi:10.1016/j.forpol.2003.08.001.
- Mousavi, S.J., and M. Shourian, Adaptive sequentially space filling meta-modeling for optimal water allocation at basin scale, *Water Resour. Res.*, in press, doi:10.1029/2008WR007076.
- Nasiri, M., Y. Niknejad, H. Pirdashti, D. Barari Tari, and S. Nasiri (2008), Growth, yield and yield traits of rice varieties in rotation with clover, potato, canola, and cabbage in North of Iran, *Asian Journal of Plant Sciences*, 7, 495-49.
- NCCO (2003), *Initial National Communication to United Nations Framework Convention on Climate Change*, 149 pp., Published by Iranian National Climate Change Office at Department of Environment, Tehran, Iran.
- NRC, National Research Council (2005), *Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop*, Committee on US-Iranian Workshop on Water Conservation and Recycling, 279 pp., The National Academic Press, Washington, D.C.
- Pazira, E., and K. Sadeghzadeh (1999), Sustainable soil and water use in agricultural sector of Iran, in, *Proceedings of 99 international conference on agricultural engineering*, Beijing, China.
- Prato, T., and G. Herath (2007), Multiple-criteria decision analysis for integrated catchments management, *Ecol. Econ.*, 63, 627-632, doi:10.1016/j.ecolecon.2007.01.003.

- Qadir, M., B.R. Sharma, A. Bruggeman, R. Choukr-Allah, and F. Karajeh (2007), Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries, *Agric. Water Manag.*, 87, 2-22, doi:10.1016/j.agwat.2006.03.018.
- Qadir, M., T.M. Boers, S. Schubert, A. Ghafoor, and G. Murtaza (2003), Agricultural water management in water-starved countries: challenges and opportunities, *Agr. Water Manage.*, 62, 165–185.
- Stads, G.J., M.H. Roozitalab, N.M. Bientema, and M. Aghajani (2008), Agricultural research in Iran: Policy, investments, and institutional profile, International Food Policy Research Institute and Agricultural Extension, Education and Research Organization, 66 pp.
- Wiek, A., and C. Binder (2005), Solution spaces for decision-making a sustainability assessment tool for city-region, *Environmental Impact assessment Review*, 25, 589-608.
- Yang, H., P. Reichert, K.C. Abbaspour, and A.J.B. Zehnder (2003), A water resources threshold and its implications for food security, *Environ. Sci. Technol.*, 37(14), 3048-3054, doi: 10.1021/es0263689.
- Yang, H., and K.C. Abbaspour (2007), Analysis of wastewater reuse potential in Beijing, *Desalination*, 212, 238–250, doi:10.1016/j.desal.2006.10.012.
- Yang, H., L. Wang, K.C. Abbaspour, and A.J.B. Zehnder (2006), Virtual water trade: an assessment of water use efficiency in the international food trade, *Hydrol. Earth Syst. Sc.*, 10, 443–454.
- Yuan, Z., Y. Zhi-feng, W. Xi-qin (2006), Methodology to determine regional water demand for instream flow and its application in the Yellow rive basin, *Journal of Environmental Sciences*, 18(5), 1031-1039, doi:10.1016/S1001-0742(06)60034-X.

6 General conclusions, study limitations, and outlook

6.1 General conclusions

The major goal of this project was to assess potential benefits of intra-country virtual water trade as a policy option to improve water productivity in Iran, taking into account natural and socio-economic constraints. A systematic analysis of water availability and water use for food production was necessary to lay the basis. The physical and process-based hydrologic model, SWAT, in combination with sequential uncertainty fitting program, SUFI-2, were found in this study quite efficient tools for the analysis. SWAT was capable of quantifying all components of the water balance including blue water flow (stream flow 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 integrated crop growth-hydrologic components in SWAT allowed quantifying the impact of agricultural water management on hydrologic water balance in different provinces. Simulation of rainfed and irrigated wheat yield, crop water consumption and crop water productivity performed well using the SWAT model. A careful calibration, validation, as well as sensitivity and uncertainty analysis were performed to improve the reliability of the model outputs. SUFI-2 program was used to calibrate the model with large number of parameters and measured data from many gauging stations. The model was calibrated against crop yield as well as river discharge taking into account dam operation. This laid the basis for systematically assessing the implications of different policies concerning water consumption and wheat production in the country. Model results were presented as 95% prediction uncertainty band. Overall, we conclude that quantification of uncertainty band is useful for decision making because of the inherent uncertainty of the input data, input parameters as well as conceptual model uncertainty (water management activities which are not included in the model).

Based on widely-used water scarcity indicators our results showed that severe water scarcity exists in about 59% of the country's land areas, where more than half of Iran's population reside. Furthermore, we found that 55% of irrigated wheat and 57% of rainfed wheat are produced in water scarce regions. The vulnerable situation of water resources availability has serious implications for the country's food security. With the analysis of different policies on water consumption-wheat production, we concluded that with the status quo situation of water resources management and considering the

increased demand due to population growth the country will be unable to produce sufficient wheat to meet the domestic demand. The analysis of impact of global climate change on future water resources availability, rainfed wheat yield, flooding and droughts showed that extreme rainfall events in the northern and western regions of the country will result in more intense flooding events in the future. On the other hand, the southern and eastern regions of the country will experience lesser rainfalls, smaller aquifer recharges, and longer periods without major rainfall events. Hence, they are susceptible to more severe drought conditions. As the irrigation is a major factor in determining the country's wheat production we concluded that wheat yields will decrease substantially in these regions if other conditions remain the same.

On the basis of these results we conclude that the current allocation of agricultural land use and the agricultural water management will not sustain wheat production in many areas because of the depletion of water resources. With global climate change the situation will worsen. This gave us the motivation to perform a systematic analysis of possible improvement in agricultural water use through implementing the VWTS considering the country has quite diverse agro-climatic, social and economic conditions. As in any other water resources management problem, restructuring of cropping pattern is faced with multiple criteria since it is necessary to consider technical, environmental, and socio-economic criteria to ensure that the outcome of the decision is favorable and lead to sustainable result. We developed a "mixed-integer, multi-objective, linear optimization model" to maximize the national cereal production under different constraints in individual provinces including land availability, water availability, and wheat consumption. Using the developed framework we examined several alternative crop production allocations corresponding to the VWT strategy. We found that Business-as-usual scenarios may hold only in a short-term, but not sustainable in the long-term due to water depletion in most parts of the country. The food security scenario cannot be sustainable because of water scarcity, unless irrigation water use efficiency would improve from the current 40% to 70%. Substantial improvement in irrigation water use efficiency suggests a promising outcome in terms of sustaining the country's total cereal production and achieving 100% wheat self-sufficiency while alleviating water stress in water scarce provinces. In the water security, scenario cereal production will decrease at national level, but increase in the provinces with high crop water productivity and large water availability. Based on the adjusted crop structures from different scenarios, we quantified the amount of virtual water that could be transferred from surplus provinces to

deficit provinces. At the national level, depending on the scenarios, wheat surplus provinces as a whole could compensate 30% to 100% of the total wheat shortage in the deficit provinces. As a result, wheat deficit provinces would receive 3.5 billion m³ to 5.5 billion m³ of virtual water by importing wheat from surplus provinces.

6.2 Study limitations

While dealing with the calibration of the large scale hydrological models, precision of the parameter estimation depends largely on the quality and quantity of the available input data. Like many other large scale modeling works, this study is subject to certain limitation in the context of data quality and quantity. The available data generally allowed obtaining satisfactory results, but inclusion of a larger number of discharge stations, and climate stations especially in the central arid part with a rather different hydrologic regime, could have improved the quality of the predictions. The inclusion of 19 large reservoirs in the model had a significant effect on the model results. Including other water management practices (more than 200 reservoirs, a number of water transfer projects, intense agricultural activities, etc.) would undoubtedly have increased model confidence could. Moreover, taking into account of more information on irrigation and related management data would have substantially improved the hydrologic water balance of the sub-basins and provinces, especially for actual ET and deep aquifer recharge. Unfortunately, there was a lack of data with respect to these factors. Thus, assumptions had to be made with respect to irrigation and related management data in the model. Data on annual planting and harvesting dates were in particular lacking. We only had data on long-term average dates. The irrigation depth and application, sources of irrigation water, and fertilizer application schedules, for individual provinces were lacking. Apart from the data that were collected locally in this study, the digital maps of landuse, soil, and DEM used in this study were obtained from a global database and thus had low resolution for Iran. Maps with a higher resolution would more likely have increased the accuracy of the model predictions.

The crop growth component of SWAT is a simplified version of the EPIC model. We found some limitations in the model structure to simulate crop yield. For instance, the default crop parameters provided in the model represent global average conditions. They can not be calibrated to reflect the exact local crop characteristics. In other words, the model has only one crop-parameter-file for the entire study area and the calibration of

a particular parameter for different regions of the project is not possible. A similar problem holds for the hydrologic parameters, which are assumed not to vary within sub-basins in the model. Thus it is not possible to account for diversity within the sub-basins, e.g. snow related parameters, climate change related parameters, etc.

The agricultural area covers only 12% of the land surface and is very scattered in Iran. According to the landuse map, agricultural land occupies a small part of each sub-basin. As the dominant landuse was assigned for each sub-basin, the agricultural areas were ignored in most sub-basins. To account for agricultural landuse, especially irrigated agriculture which had a significant importance in the model, we “manually” assigned certain crops to entire sub-basins. This resulted in some overestimation of the agricultural area compared to reality. However, this did not negatively influence the results in general as most of the crop related output data are area-independent variables (e.g. *CWP* (kg m^{-3}), yield (ton ha^{-1})). However, aggregating the hydrological components (i.e. ET, soil water) from sub-basin to provincial level might not have fully representative results. The reason is that sub-basins with only a small fraction of agriculture in reality will be entirely dominated by the crops grown in that fraction in the model. This point might have significant implications when it comes to critical issues concerning sub-basin-based water management. A higher resolution representative agricultural area of sub-basins will increase the reliability of the model.

6.3 Outlook

In addition to the current imbalances between water availability and water demand in Iran, deteriorating ground and surface water quality is also of critical concerns. Freshwater bodies have limited capacity to support the pollutant charges of the effluents from expanding urban, industrial and agricultural uses. This exacerbates water scarcity. For example, the Karoun River, which is the most navigable river in southwestern Iran, is contaminated by wastewater, agricultural, and industrial discharges. It is reported that the drained water from irrigated land has high concentrations of fertilizers, heavy metals, suspended and dissolved solids, and pesticides (Nadaffi, 2007). A similar situation has been reported for many other parts of the country, in particular provinces with a high potential for agricultural and industrial developments. Thus, we intend to expand the hydrologic model developed here to include also water quality. This is

important for a sustainable management of the country's water resources in the face of the ongoing scarcity issues.

In view of the current trend in global climate change and its potential impacts on water resources, it is of strategic importance also to assess the impact of climate change on crop yield and water consumption. This would be essential for the country's future water and food management and planning. It is reported that climate change will pose a serious threat to agricultural production in arid areas (IPCC, 2007). The impacts on yield will vary by crop types, location and times. (Thornton et al., 2009). Studies on such impacts have been conducted for various regions in the world (e.g. Mo et al., 2009). However, there is lack of information on the impact of climate change on crop systems in Iran. Our approach could be used to assess the impact of future climate change on crop yield and water consumption for Iran. Our model also allows accounting for inherent uncertainty of climate models as well as scenarios in predicting water and food relations.

Sedimentation of eroded soil is one of the greatest water pollution processes by volume entering to the lakes, rivers, and wetlands. In the same time erosion represents a substantial loss of soil fertility. The consequences are decline in crop yield, decrease in storage capacity of dams, degradation of river water quality, and increase in flood frequency (Rostamian, 2008; Safamanesh, 2006). Farming, logging, and construction activities are the major drivers of erosion and off-site sedimentation. Development of effective solutions to minimize soil erosion and sedimentation is essential for a sustainable soil and water management in the country. As our hydrological model was not calibrated for sediment yield, one of the main objectives in a further research project should be a modeling of the country's soil erosion.

Rangelands play an important role for food security as well as for soil protection in Iran. Iranian rangelands have suffered from: overgrazing, untimely grazing and destruction of pastures by conversion into arable land (Farahpour et al., 2004; Azadi et al., 2009; Mashayekhi, 1990). Therefore, it is important to include grazing issues and rangeland management in the SWAT model of Iran to lay the basis for a sustainable management of water and land resources toward food security. It would be worthwhile to account for the virtual water content of one kilogram of meat with a high spatial and temporal resolution. As meat is one of the major components of Iranian diets, a systematic analysis on the virtual water content of meat, produced in different provinces/regions, will further elucidate the impact of the Iranian food consumption patterns on the water scarcity in Iran.

References

- Azadi, h., van den Berg., J., Shahvali, M., Hosseininia, G., 2009. Sustainable rangeland management using fuzzy logic: a case study in Southwest Iran, *Agriculture, Ecosystems and Environment*, 131, 193-200.
- Farahpour, M., van Keulen, h., Sharifi, M.A., Bassiri, M., 2004. A planning support system for rangeland allocation in Iran with case study of Chadegan sub-region, *Rangeland Journal*, 26-225-236.
- IPCC, 2007. *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, Martin L., Canziani, Osvaldo F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 1000 pp.
- Mashayekhi, A.N., 1990. Rangeland destruction under population growth, *System Dynamics Review*, 6, 167-193.
- Mo, X., Liu, S., Lin, Z., Guo, R., 2009. Regional crop yield, water consumption and water use efficiency and their responses to climate change in the North China Plain, *Agriculture, Ecosystems and Environment*, 134, 67-78.
- Naddafi, k., Honari, H., Ahmadi, M., 2007. Water quality trend analysis for Karoon river in Iran, *Environmental Monitoring and Assessment*, 134, 305-312.
- Rostamian, R., Jaleh, A., Afyuni, M., Mousavi, S.F., Heidarpour, M., Jalalian, A., Abbaspour, K.C., 2008, Application of SWAT model for estimating runoff and sediment in two mountainous basins in central Iran, *Hydrological Sciences Journal*, 53, 977-988.
- Safamanesh, R., Sulaiman, W.N.A., Ramli, M.F., 2006. Erosion risk assessment using an empirical model of Pacific South West Inter Agency Committee method for Zargeh watershed, Iran, *Journal of Spatial Hydrology*, 6, 105-120.
- Thornton, P.K., Jones, P.G., Alagarswamy, G., Andresen, J., 2009. Spatial variation of crop yield response to climate change in East Africa, *Global Environmental Change*, 19, 54-65.

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