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Water footprint assessment of main cereals in Iran

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ABSTRACT

Iran is mostly located in arid and semiarid regions which makes agricultural water management considerably important in this country. In this research the concept of 'water footprint' (WF) is applied at the regional scale for the first time in the country. The calculation framework of Ababaei and Ramezani Etedali (2014) was adopted and modified to better account for the gray and white WFs. The weighted average of each WF component (green, blue, gray and white) and the national total water footprint (NTWF) of the production of main cereals (wheat, barley and maize) were calculated. The NTWF of wheat, barley and maize production were estimated 36,777, 7975 and 3744 million cubic meters (MCM) per year for the period 2006–2012. The ratio of total green WF of three crops to the aggregated NTWF (i.e. all crops) was 43%, and the ratios of the green WF to the NTWF were 47%, 42% and 2% for wheat, barley and maize, respectively. These results show that wheat and barley production are significantly large consumers of the green water resources (i.e. effective precipitation). This implied that there are great opportunities to improve the green water productivity through increasing yield, especially in wheat and barley rainfed lands. The average national green+blue WFs were estimated 24,628, 5,123 and 1,604 MCM per year for wheat, barley and maize, respectively, and 31,356 MCM per year altogether. The ratios of national gray + white WF to the NTWF were also estimated 33%, 36% and 57% for wheat, barley and maize, respectively. These values show the importance of better irrigation management strategies to reduce the share of gray and white WF which is important in both terms of water resources management and environment conservation.

1. Introduction

Increasing populations, socioeconomic developments, global freshwater withdrawal, dying rivers and high pollution levels are all signs of growing water scarcity (Gleick, 1993 Postel, 2000; WWAP, 2009; Mekonnen and Hoekstra, 2010). Agriculture is the main user of fresh water with 85% of global surface and ground water consumption (Shiklomanov, 2000; Molden, 2007) and reducing the consumptive water use in this important sector of economy is part of all major strategies related to relieving water scarcity (Chukalla et al., 2015). To this end, major efforts have been dedicated to reducing the non-beneficial consumptive water use and the non-recoverable water losses (e.g. Hoekstra, 2003; Falkenmark and Rockström, 2006) which at the same time can result in increasing water productivity (Molden, 2007).

The water footprint concept, first introduced by Hoekstra (2003) and later elaborated by Hoekstra and Chapagain (2008), is recently being used for fresh water resources management (Wackernagel and Rees, 1996; Wackernagel et al., 1997; Wackernagel and Jonathan, 2001; Ababaei and Ramezani Etedali, 2014). The water footprint (WF) of a product (usually known as virtual water content) is defined as the volume of water consumed or polluted for producing the product, measured over its full production chain and is an indicator of the allocation of freshwater resources to different part of the production process.

Knowledge of how allocated water resources are consumed over the production process is highly valuable for water resources managers and policy makers. Many studies have focused on virtual water and virtual water transfer (Hoekstra and Hung, 2002, 2005; Hoekstra and Chapagain, 2007, 2008; Liu et al., 2007) and some distinguished green (i.e. effective precipitation) and blue (i.e. irrigation) water components (Liu et al., 2009; Liu and Yang, 2010; Siebert and Doll, 2008, 2010; Liu et al., 2007, 2009; Gerbens-Leenes et al.,

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2009; Aldaya et al., 2010; Ababaei and Ramezani Etedali, 2014). The gray WF, which was introduced in order to express water pollution in terms of a volume polluted (Hoekstra et al., 2011), was first used for the analysis of the WF of wheat in different regions of Italy by Aldaya and Hoekstra (2010).

Water footprint can be decreased through increasing yields, using more efficient irrigation systems (like drip irrigation), reducing non-beneficial evapotranspiration (e.g. by using mulches), reducing fertilizer loss, enhancing effective use of precipitation, optimizing crop planting dates and choosing crops and varieties with higher yield (Zhuo et al., 2016; Chukalla et al., 2015). Zhuo et al. (2016) estimated green, blue and gray WF in Yellow river basin for the period 1961–2009 and showed the sum of green and blue WFs has reduced due to improved crop yields and the gray WF increased because of the growing use of fertilizers. Also they concluded that the ratio of blue to green WF has increased due to expansion of irrigated lands.

Ababaei and Ramezani Etedali (2014) used the framework proposed by Hoekstra et al. (2009) and introduced a new term, the white WF, for wheat irrigated lands as an indicator of irrigation water losses and showed that the national total WF (NTWF) of Iran's wheat production for the period 2006–2012 is around 42,143 million cubic meters (MCM) per year (including 16% gray and 25% white WF). Their results suggest that the investigations of the gray and white WF are essential in production of main cereals.

Most of the studies on virtual water and water footprint in Iran have been limited to one specific crop or small study areas (e.g. Dehghanpur and Bakhshoodeh, 2008; Babazadeh and Sarai Tabrizi, 2012; Pourjafarinejad et al., 2013; Arabi Yazdi et al., 2015; Omidi and Homaee, 2015) which cannot provide policy-makers with accurate information on how water resources are used. There are only a few comprehensive studies which consider more than one crop and spatial variations of climate, soil and management (e.g. Montazar et al., 2009; Ababaei and Ramezani Etedali, 2014). Hence, the purpose of this study is to estimate the green, blue, gray and white WFs of the main cereals (wheat, barley and maize) in the main cereal producing provinces of Iran at the provincial and national levels. We quantify different WF components of crop production using a regional water balance model, AGWAT, which calculates the crop water requirements and actual water use taking into account local climate, soil conditions and irrigation management strategies.

2. Materials and methods

The national green, blue, gray and whitewater footprints of wheat, barley and maize production were estimated following the calculation frameworks of Hoekstra and Chapagain (2008) and Hoekstra et al. (2009), and modifications proposed by Ababaei and Ramezani Etedali (2014). Within this framework, the WF is considered as an indicator of the allocation of water by humanity and hence the consumption by ecosystems is not considered a WF (Hoekstra et al., 2011). Irrigation requirements and effective precipitation were estimated using the AGWAT model (IRIMO, 2001) which calculates crop evapotranspiration (ET, in mm) and irrigation requirements using FAO-Penman-Monteith method under standard and non-standard conditions (Allen et al., 1998). The model was applied at the regional scale (for the first time in the country) using the input data available in the model database. Irrigation was triggered when 50% of the total available water was depleted and filled the root zone moisture content back to the field capacity. As effective precipitation (P_{eff}, in mm) is not provided in the database, the net irrigation requirements (IR, in mm) were first calculated by considering gross irrigation requirement (GI, in mm) and average irrigation efficiency (IE, dimensionless) in each region. Average irrigation efficiencies were provided in the model database as the values used by local authorities for regional water resources planning. Total effective precipitation was calculated as the difference between the actual crop evapotranspiration (ET_c, in mm) and the net irrigation requirements (IR), which were both extracted from the model database. The green and blue water uses (CWU, in m^3/ha) were considered equal to the net irrigation requirement and effective precipitation (Eqs. (1)–(4)). Obviously, no blue water use was considered under rainfed conditions:

$$CWU_{Blue,Irr} = IR = 10 \times IE \times GI \tag{1}$$

$$CWU_{Green,Irr} = 10 \times P_{eff} = 10 \times (ET_c - IR) \tag{2}$$

$$CWU_{Blue,RF} = 0 \tag{3}$$

$$CWU_{Green,RF} = 10 \times P_{eff} \tag{4}$$

Where the RF and Irr subscripts show rainfed and irrigation conditions, respectively. Next, the green (WF_{Green}) and blue (WF_{Blue}) water footprints (in m^3/ton) were calculated by dividing the green and blue CWU (in m^3/ha) by actual crop yield (in ton/ha) separately under rainfed and irrigated conditions. Irrigated and rainfed yields of wheat, barley and maize were obtained from the Ministry of Agricultural-Jihad for the period 2006–2012 at a provincial scale.

Volume of water required to assimilate the fertilizers leached in run off is called the gray WF (Hoekstra, 2003). In this study, the gray water footprint (WF_{Gray}) related to nitrogen application was only estimated as the main source of pollution in agricultural area in Iran (Eqs. (5)–(6)). The nitrogen application rates (NAR, in kg/ha) were obtained from the Ministry of Agricultural-Jihad. The WF_{gray} (m^3/ton) was calculated following Chapagain et al. (2006) and Hoekstra et al. (2011). The USEPA standard was considered (Chapagain et al., 2006) for the maximum allowable concentration (C_{Max}, in mg/L) of nitrate in surface and groundwater which recommends a maximum concentration of 10 mg/L. This standard was adopted since most of the agricultural water is extracted from and returned to the same resources used for domestic purposes and pollution needs to be kept below an acceptable threshold. The natural nitrogen concentrations (C_{Nat}, in mg/L) were conservatively assumed to be zero as no data or model simulations was available at this spatial scale.

$$WF_{Gray,Irr} = \frac{\alpha_{Irr} \times NAR_{Irr}}{C_{Max} - C_{Nat}} \times \frac{1}{Yield_{Irr}} \tag{5}$$

$$WF_{Gray,RF} = \frac{\alpha_{RF} \times NAR_{RF}}{C_{Max} - C_{Nat}} \times \frac{1}{Yield_{RF}} \tag{6}$$

The α values were assumed to be equal to the values applied by Chapagain et al. (2006) and Hoekstra et al. (2011), i.e. 10% and 5% of the total nitrogen fertilizer applied under irrigated and rainfed conditions, respectively. Moreover, the irrigation loss (only that part which is not considered as the gray WF, m^3/ton) was considered as part of the total WF and referred to by the term "white water footprint" (WF_{White}, in m^3/ton). The equations used here to calculate the white WF are different with those first proposed by Ababaei and Ramezani Etedali (2014) in order to consider the contribution of the white WF to the gray WF. This modification was deemed necessary as deep percolation assimilates fertilizers in the soil. A part of irrigation water (called leaching requirement) is usually applied by farmers to control soil salinity and keep yield reduction below an acceptable level. This part is considered as the gray WF. The remaining part of the white WF is assumed lost since in most regions of the country water table is now deeper than 50 m (and is going deeper at the average rate of ~1 m/year) and it takes years for this water to return to the source.

$$WF_{White,Irr} = max(0, \frac{10 \times (GI - IR)}{Yield_{Irr}} - WF_{Gray,Irr}) \tag{7}$$

$$WF_{White,RF} = 0 \tag{8}$$

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