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ORIGINAL ARTICLE

Estimation of Water Footprint Components of Iran's Wheat Production: Comparison of Global and National Scale Estimates

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Abstract The water footprint (WF) of national wheat production has been previously estimated for the whole world in global-scale studies. These studies used assumptions which must be assessed and evaluated by estimates from national or regional studies. Here, previous estimates of different components (green, blue, gray and white) of WF of national wheat production in Iran were compared to the national-scale estimates. A new component (white WF) was proposed to account for the irrigation losses. Different components of the wheat WF were estimated for 236 plains over fifteen major wheat producing provinces. Then, the average values of each province were estimated. Finally, the weighted average values of each WF component were estimated by using the shares of irrigated and rainfed productions as weighting factors. The average total WF for irrigated areas and between all selected provinces is about 3,188 m^3/ton with comparable shares of blue and green water, while the average total WF for rainfed areas is about 3,071 m^3/ton with the share of the green WF nine times that of the gray WF. The results show that the total national WF of wheat production for the period 2006–2012 is about 42,143 million cubic meters (MCM) per year (41 % green, 18 % blue, 16 % gray and 25 % white) with the share of the green WF about 2.3 times the blue WF. Comparison of the obtained estimates with the results of the previous studies at a global scale revealed that estimating the WFs of crops at a global scale, ignores the variations of climatic conditions, water resources availability and crop yields at the national and regional levels and some of the assumptions made in global-scale studies must be reassessed.

Keywords Virtual water · Water footprint · Wheat · Provincial scale · National scale

1 Introduction

Freshwater resources show enormous time and spatial variability from the viewpoints of availability and quality. Growing populations combined with socioeconomic developments

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put pressure on scarce water resources. Water consumption and pollution have exceeded the critical level in many parts of the globe (Mekonnen and Hoekstra 2010). Groundwater depletion, dying rivers and high pollution levels are all signs of growing water scarcity (Gleick 1993; Postel 2000; WWAP 2009). If humankind is to meet the challenges over the coming 50 years, the water use in agriculture has to be substantially reduced (Molden 2007).

In recent years, a new framework has been provided through the introduction of the “water footprint” (WF) concept by Hoekstra (2003), in analogy to the ecological footprint concept (Wackernagel and Rees 1996; Wackernagel *et al*. 1997; Wackernagel and Jonathan 2001). The concept was elaborated by Hoekstra and Chapagain (2008) and enables one to analyze the connection between human consumption and the allocation of the freshwater resources.

The WF of a product is defined as the total volume of freshwater that is used to produce the product (Hoekstra *et al*. 2011). The blue WF refers to the consumed (evaporated) volume of surface and/or groundwater in the production process of a good, and the green WF refers to the rainwater consumed. Hoekstra *et al*. (2009) define the gray WF of a product as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

The virtual water content of a product is the freshwater ‘embodied’ in the product in virtual sense (Hoekstra *et al*. 2011). It refers to the volume of water consumed or polluted for producing the product, measured over its full production chain. Virtual water transfer, is a mechanism to save domestic water resources and achieve national water security (Allan 2003; Hoekstra 2003; De Fraiture *et al*. 2004; Liu *et al*. 2007; Oki and Kanae 2004; Chapagain *et al*. 2006; Yang *et al*. 2006; Hoekstra and Chapagain 2008). For example, international trade of agricultural commodities by importing water-intensive products and exporting water-extensive commodities results in saving scarce domestic water resources (Mekonnen and Hoekstra 2010). On the other hand, exporting water-intensive commodities brings considerable profits for water-abundant countries.

In this paper, the focus is on the WF components of wheat production, as one of the most widely cultivated cereal grains globally. Hoekstra and Hung (2002; 2005) assessed the wheat production water use at a global scale in the period 1995–1999, and looked at total evapotranspiration (ET). Hoekstra and Chapagain (2007, 2008) made a similar assessment for the period 1997–2001. Liu *et al*. (2007) made a grid-based global assessment of water consumption in wheat production for the period 1998–2002. None of these three studies distinguished between green and blue water components. Liu *et al*. (2009) and Liu and Yang (2010) made a similar analysis with the green-blue water distinction. The global water consumption for wheat production with the green-blue water distinction was estimated by Siebert and Doll (2008; 2010) using a grid-based approach for the same period as Liu *et al*. (2007; 2009). Gerbens-Leenes *et al*. (2009) estimated the green and blue WF for wheat in the 25 largest producing countries. Aldaya *et al*. (2010) have estimated the green and blue water components for wheat in four major producing countries, and also estimated wheat-trade-related international virtual water flows. Aldaya and Hoekstra (2010) made an analysis of the WF of wheat in different regions of Italy, for the first time specifying the gray WF as well.

The water footprint of national wheat production was estimated previously for the whole world. Global-scale studies made assumptions which must be assessed and evaluated by the estimates from national or regional studies. Hence, this study aims to estimate the green, blue and gray WF of wheat in Iran, from a production perspective. These components were estimated at the regional scale and compared to the global-scale estimates. Furthermore, a new WF component (white) is proposed which accounts for the irrigation losses.

2 Materials and Methods

In this study, the national green, blue, gray and white water footprint of wheat production were estimated following the calculation framework of Hoekstra and Chapagain (2008) and Hoekstra *et al*. (2009) with a few modifications. The estimations of crop ET and irrigation requirements under non-standard conditions have been done following the method and assumptions provided by Allen *et al*. (1998). The irrigation requirements and effective rainfall were estimated using the AGWAT model (IRIMO 2001). AGWAT is designed for the estimation of crop irrigation requirements under standard and non-standard conditions (Allen *et al*. 1998). The model was applied at a plain scale using the input data available in the model database. Irrigation was triggered whenever the root zone moisture depletion reached 50 % of the total moisture available and filled the root zone moisture content back to the field capacity. Since the AGWAT calculates the gross irrigation requirements (GI_{Irr}) for each 10-day period, the net irrigation requirements (IR_{Irr}) were first calculated by considering irrigation efficiency (IE_{Irr}) of each plain. Then, total effective precipitation (P_{eff}) was calculated as the difference between total actual crop evapotranspiration ($ET_{c.}$) and the total net irrigation requirements (IR_{Irr}). After that, the green and blue crop water uses (CWU) were estimated by the following equations:

$$CWU_{Blue,Irr} = IR_{Irr} = 10 \times IE_{Irr} \times GI_{Irr} \tag{1}$$

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

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

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

where: *Irr* and *RF* refer to irrigated and rainfed conditions, respectively; and 10 is the conversion factor from mm to m^3/ha. The green (WF_{Green}) and blue (WF_{Blue}) water footprints (m^3/ton) are calculated by dividing the green and blue *CWU* (m^3/ha), respectively, by the actual crop yield (ton/ha). Since the yields are different under irrigated and rainfed conditions, the calculation of WF components were done with the respective actual yields under each condition. All WF components were estimated for all the plains (except for the provinces with more than 30 plains) in fifteen major wheat producing provinces (Table 1) which produce more than 86 % of national wheat productions. For provinces with more than 30 plains, the plains with unique combinations of planting date and representative climatic stations were chosen. Irrigated and rainfed yields were obtained from Agricultural-Jihad Ministry (AJM) for the period 2006–2012 at a provincial scale.

Another component of the wheat production WF is the volume of water required to assimilate the fertilizers leached in runoff (gray WF). In this study, the gray water footprint (WF_{gray}) related to nitrogen application was only estimated to make the results comparable to those from studies on a global scale. The WF_{gray} of wheat (m^3/ton) is calculated by the following equations:

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

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

As the main purpose of this study was to compare the national and global estimates of WF components, the α values were assumed to be equal to the values applied by Chapagain *et al.* (2006) and Hoekstra *et al.* (2011)., i.e. on the average 10 % and 5 % for the applied nitrogen

Table 1 Wheat production data for the major wheat producing provinces

Province	Production (ton)			Share (%)		National Share (%)			Yield (kg/ha)	
	Irrigated	Rainfed	Total	Irrigated	Rainfed	Irrigated	Rainfed	Total	Irrigated	Rainfed
Ardebil	329,954	270,715	600,668	54.9	45.1	3.8	6.5	4.6	4,240	1,145
Eastern Azerbaijan	283,104	287,902	571,006	49.6	50.4	3.2	6.9	4.4	3,014	861
Fars	1,578,195	103,768	1,681,962	93.8	6.2	18.0	2.5	13.0	4,058	817
Golestan	475,667	442,123	917,790	51.8	48.2	5.4	10.5	7.1	3,067	2,021
Hamadan	352,909	333,758	686,666	51.4	48.6	4.0	8.0	5.3	3,864	1,033
Kermanshah	384,030	417,436	801,466	47.9	52.1	4.4	10.0	6.2	4,638	1,192
Khorasan	994,297	206,968	1,201,265	82.8	17.2	11.3	4.9	9.3	2,900	624
Khuzestan	1,254,269	93,022	1,347,291	93.1	6.9	14.3	2.2	10.4	2,994	498
Kurdestan	149,478	492,957	642,435	23.3	76.7	1.7	11.8	5.0	4,149	993
Lorestan	215,306	291,500	506,806	42.5	57.5	2.5	7.0	3.9	3,102	1,179
Markazi	286,251	169,691	455,941	62.8	37.2	3.3	4.0	3.5	3,800	943
Qazvin	255,899	77,380	333,278	76.8	23.2	2.9	1.8	2.6	4,045	894
Tehran	424,140	2,694	426,834	99.4	0.6	4.8	0.1	3.3	4,764	1,010
Western Azerbaijan	332,104	283,664	615,769	53.9	46.1	3.8	6.8	4.7	3,122	1,037
Zanjan	85,351	341,459	426,810	20.0	80.0	1.0	8.1	3.3	3,700	965
Total (15 Provinces)	7,400,951	3,815,035	11,215,987	66.0	34.0	84.3	91.0	86.5	3,508	1,049
Total (National)	8,778,996	4,192,808	12,971,804	67.7	32.3	–	–	–	3,438	1,010

fertilizer under irrigated and rainfed conditions, respectively. Also, the maximum value (C_{Max}) of nitrate in surface and ground water is recommended at 50 mg/L nitrate (NO3) or 10 mg/L as nitrate-nitrogen (NO3-N) by the World Health Organization and USEPA, respectively. In this study, the USEPA standard was considered (Chapagain *et al.* 2006). The natural nitrogen concentrations (C_{Nat}) were assumed to be zero.

Moreover, the irrigation loss (m^3/ha) was considered as a part of wheat WF and was named as "white water footprint":

$$WF_{White,Irr} = \frac{10 \times (GI_{Irr} - IR_{Irr})}{Yield_{Irr}} \tag{7}$$

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

The green, blue, gray and white WFs of wheat production for each province were estimated by taking the average WF (m^3/ton) over the respective plains. Finally, the national WF components of wheat production were estimated by taking the average of each component over all the provinces weighted by the share of each province in the whole wheat production of the selected provinces, according to the data obtained from AJM.

After estimating the WF components (m^3/ton) for each selected provinces, the total volumes of each component in each province and the national volumes of each component were calculated as the weighted average of the WFs under irrigated and rainfed conditions, using following equations:

$$WFV_{i,x,y} = \text{Pr}od_{i,x,y} \times WF_{i,x,y} \qquad i = 1, \ldots, 15 \tag{9}$$

$$AWF_{x,y} = \frac{\sum_i WFV_{i,x,y}}{\sum_i \text{Pr}od_{i,x,y}} \tag{10}$$

$$WAWF_x = \beta . AWF_{x,Irr} + (1-\beta) AWF_{x,RF} \tag{11}$$

$$NWF_x = Tot\text{Pr}od . WAWF_x \tag{12}$$

where: *i*: province index; *x*: green, blue, gray or white; *y*: *Irr* (irrigated) or *RF* (rainfed); *Prod*: wheat production (Mton); *WFV*: the total volumes of each WF components (million cubic meters, MCM); *AWF*: the average values of each WF component (m^3/ton); β: the share of irrigated wheat production in the whole country (0.677); *WAWF*: the weighted average values of each WF component (m^3/ton); *TotProd*: total wheat production (Mton); and *NWF*: the total national volumes of each WF components (MCM).

3 Results

Data on wheat production and nitrogen application rates (*NARs*) in fifteen major producing provinces is shown in Tables 1 and 2, respectively. In 2006–2012, more than 67 % of the national wheat production was irrigated and 32.3 % was rainfed, on the average, while 37.9 % was irrigated and 62.1 % was rainfed from more than 6,568 Kha of wheat cultivated lands.

Different components of wheat WF were estimated for 236 plains over fifteen selected provinces (Table 3, Figs. 1 and 2). For irrigated areas, the green WFs ranged from 499 to 1,023 m^3/ton, the blue WFs from 521 to 1,402 m^3/ton, the gray WFs from 337 to 822 m^3/ton,

Table 2 Nitrogen application rates for selected provinces (2006–2012)

Province	NAR (kg/ha) [1]	
	Irrigated	Rainfed
Ardebil	267.9	23.0
Eastern Azerbaijan	111.3	43.7
Fars	333.7	65.3
Golestan	160.1	126.8
Hamadan	161.6	55.2
Kermanshah	261.4	83.6
Khorasan	192.5	17.0
Khuzestan	230.8	73.7
Kurdestan	156.4	54.4
Lorestan	154.7	81.6
Markazi	235.4	83.4
Qazvin	202.7	26.0
Tehran	228.3	25.0
Western Azerbaijan	105.1	31.1
Zanjan	193.4	94.2

[1] Source: Agricultural-Jihad Ministry

and the white WFs from 701 to 2,301 m^3/ton. The average total WF for irrigated areas among all selected provinces is about 3,188 m^3/ton, with almost equal shares of blue and green water (Table 4). For rainfed areas, the green WFs ranged from 1,282 to 4,166 m^3/ton and the gray WFs from 100 to 740 m^3/ton. The average total WF for rainfed areas is about 3,071 m^3/ton with the share of the green WF nine times the gray WF (Table 4).

Table 5 and Fig. 2 present the final estimation of national average values of different WF components. The weighted average values (*WAWF*) are calculated by Equation (11). The (G) sign indicates the values estimated by Mekonnen and Hoekstra (2010) via a global assessment. As it can be seen, Mekonnen and Hoekstra (2010) estimated the green, blue and gray components of wheat production in Iran equal to 2,412, 988 and 290 m^3/ton, respectively. Here, the estimates of these components are revised to 1,328, 571 and 525 m^3/ton, respectively.

The total national WF (*NWF*) of wheat production for the period 2006–2012 is estimated at 42,143 MCM/year (41 % green, 18 % blue, 16 % gray and 25 % white). About 86.3 % of the total NWF related to wheat production is related to these fifteen provinces (Fig. 3). Fars (13.2 %), Khorasan (11.9 %) and Khuzestan (9.8 %) constitute 34.9 % of the total *NWF* related to the wheat production. In irrigated areas, these three provinces constitute 14.5 %, 50.4 %, 43.0 % and 52.1 % of the total green, blue, gray and white WFs related to the wheat production, respectively. In rainfed areas, the largest green WFs can be found in Kurdistan (9.2 %), Kermanshah (6.6 %) and Zanjan (5.7 %). While the largest gray WFs are related to Tehran (2.4 %), Hamadan (2.1 %) and Kurdistan (2 %).

When consumptive water use (blue plus green WFs) is only considered, the WFs of wheat from rainfed and irrigated land are nearly equal. Similar conclusion was reached by Mekonnen and Hoekstra (2010). Although yields are considerably higher in irrigated areas, crop evapotranspiration ($ET_{c.}$) is higher in these areas as well. In rainfed areas, the $ET_{c.}$ over the growing period is lower than the potential evapotranspiration (ET_p), while under irrigated conditions there is more water available to meet crop water requirements, leading to an $ET_{c.}$ near or equal to ET_p.

Table 3 Water footprint components of wheat production for the major wheat producing provinces

Province	Water Use (mm)			WF_{Irr} (m^3/ton)					WF_{Irr}(m^3/ha)	WF_{RF} (m^3/ton)		
	$ET_{c.}$	IR	P_{eff}	Green	Blue	Gray	White	Total	Gray	Green	Gray	Total
Ardebil	494.1	231.8	262.1	618	547	632	854	2,651	11,213	2,289	100	2,390
Eastern Azerbaijan	536.3	290.3	246.1	817	963	369	1,243	3,391	10,291	2,860	254	3,113
Fars	607.1	364.7	242.4	597	899	822	1,214	3,533	14,537	2,967	400	3,367
Golestan	418.8	159.5	259.0	845	521	522	773	2,661	8,216	1,282	314	1,596
Hamadan	574.3	313.1	261.1	676	811	418	1,016	2,921	11,269	2,527	267	2,794
Kermanshah	591.7	267.4	324.4	699	576	564	804	2,643	12,315	2,721	351	3,072
Khorasan	606.5	406.5	200.0	690	1,402	664	2,301	5,056	14,661	3,205	137	3,341
Khuzestan	425.8	218.3	207.5	693	729	771	1,094	3,287	9,771	4,166	740	4,906
Kurdestan	697.4	376.5	320.7	773	908	377	1,346	3,404	14,235	3,231	274	3,505
Lorestan	631.2	313.8	317.5	1,023	1,011	499	1,632	4,165	12,844	2,693	346	3,039
Markazi	555.4	301.7	253.8	668	794	619	1,039	3,120	11,875	2,692	442	3,134
Qazvin	569.5	299.9	269.2	666	742	501	877	2,786	11,264	3,012	145	3,158
Tehran	509.5	272.0	237.6	499	571	479	701	2,250	10,719	2,352	123	2,475
Western Azerbaijan	493.0	218.6	274.6	880	700	337	956	2,872	8,998	2,648	150	2,798
Zanjan	553.9	275.3	278.5	753	744	523	1,067	3,086	11,418	2,887	488	3,375
Average	551.0	287.3	263.6	726	794	540	1,128	3,188	11,575	2,769	302	3,071
CV	13 %	22 %	13 %	17 %	28 %	25 %	35 %	21 %	16 %	21 %	55 %	22 %
Min	418.8	159.5	200.0	498.8	520.9	336.7	701.3	2,249.9	8,216.0	1,281.9	100.4	1,595.6
Max	697.4	406.5	324.4	1,023.4	1,401.8	822.3	2,300.9	5,056.4	14,661.0	4,165.8	740.3	4,906.2

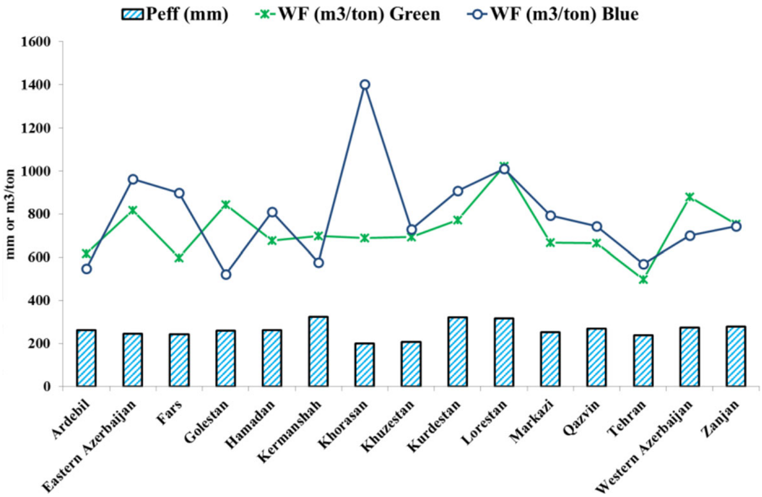

Fig. 1 Green and blue water footprints (WF) of wheat production and effective precipitation (P_{eff}) for the major wheat producing provinces (2006–2012)

4 Discussion

The results of the current study with respect to the total national WF of wheat production can be compared to three previous global studies: the studies by Mekonnen and Hoekstra (2010), Liu *et al*. (2007) and Chapagain and Hoekstra (2004). The two latter studies did not take a grid-based approach and also did not make the green-blue distinction. The estimate of the total water footprint (blue + green) by Liu *et al*. (2007), 1,776 m^3/ton, is 6 % lower and the estimate by Chapagain and Hoekstra (2004) (i.e. 2,925 m^3/ton) is 54 % higher than our estimate. The GEPIC model tends to give lower estimates of ET compared to other models (Hoff *et al*. 2010), and this could be the reason of relatively lower values estimated by Liu *et al*. (2007). Chapagain and Hoekstra (2004) applied the model of Allen *et al*. (1998) which is the base of the AGWAT model.

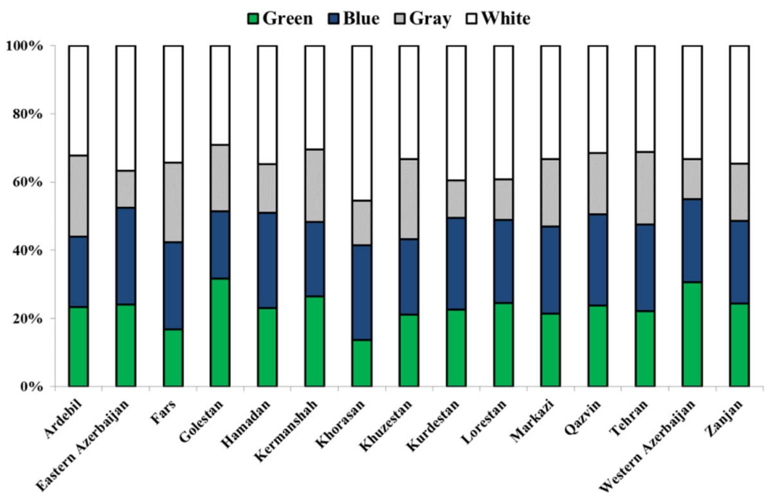

Fig. 2 The share of different WF components for the major wheat producing provinces

Table 4 The share of different WF components for the major wheat producing provinces

Province	WF_{Irr} (%)				WF_{RF} (%)	
	Green	Blue	Gray	White	Green	Gray
Ardebil	23	21	24	32	96	4
Eastern Azerbaijan	24	28	11	37	92	8
Fars	17	25	23	34	88	12
Golestan	32	20	20	29	80	20
Hamadan	23	28	14	35	90	10
Kermanshah	26	22	21	30	89	11
Khorasan	14	28	13	46	96	4
Khuzestan	21	22	23	33	85	15
Kurdestan	23	27	11	40	92	8
Lorestan	25	24	12	39	89	11
Markazi	21	25	20	33	86	14
Qazvin	24	27	18	31	95	5
Tehran	22	25	21	31	95	5
Western Azerbaijan	31	24	12	33	95	5
Zanjan	24	24	17	35	86	14
Average	23	25	17	35	90	10
CV	19	10	27	12	5	47

The model of Allen *et al*. (1998) applies a runoff model and its results affect the soil water balance and soil water availability, and eventually, the calculation of green water footprint, while AGWAT does not calculate this kind of losses directly and uses the concept of effective precipitation. Besides, Liu *et al*. (2007) estimated water footprints (m^3/ton) based on the simulated yields, whereas the actual yields were used in the present study. For estimating daily reference ET in this study, long-term monthly average reference ET values from the nearest climatic stations were used, while Chapagain and Hoekstra (2004) obtained the climatic data from the on-line database of the Tyndall Centre for Climate Change and Research (Mitchell and Jones 2005). As there are considerable spatial variations among the studied plains and provinces, the average data at a national scale could result in biased estimates of WF components.

Mekonnen and Hoekstra (2010) estimated the green, blue and gray WFs at 2,412, 988 and 290 m^3/ton, compared to our estimates of 1,328, 571 and 525 m^3/ton, respectively. Their estimated green and blue components are 82 % and 73 % higher and the gray component 45 % lower than our estimates. They used a grid-based dynamic water balance model to calculate *CWU* and yield over time, while in the current study, the actual average yields at a provincial scale were combined with a calibrated model (AGWAT) for estimating the irrigation requirements. Of course, this is not the main cause for these differences. It is believed that Mekonnen and Hoekstra (2010) estimated the weighted values of different WF (*WAWF*) components in a questionable way. Mekonnen and Hoekstra (2010) proposed an equation similar to equation (11) which used the irrigated and rainfed fraction of wheat area in each grid cell as the weighting factors, while the *WAWFs* are related to the relative productions of these areas, not their shares of cultivated areas. Another reason for these differences is that Mekonnen and Hoekstra (2010) used wheat crop coefficients, planting dates and lengths of cropping season from the studies of Chapagain and Hoekstra (2004), Sacks *et al*. (2009) and Portmann *et al*. (2008). All these studies presumed the same values for the whole cultivated areas, while, our

Table 5 The total volumes of each WF components for the major wheat producing provinces

Province	WFV_{Irr} (MCM)					WFV_{RF} (MCM)		
	Green	Blue	Gray	White	Total	Green	Gray	Total
Ardebil	204	181	208	282	875	620	27	647
Eastern Azerbaijan	231	272	105	352	960	823	73	896
Fars	942	1,418	1,298	1,917	5,575	308	41	349
Golestan	402	248	248	368	1,266	567	139	705
Hamadan	238	286	148	359	1,031	843	89	933
Kermanshah	269	221	216	309	1,015	1,136	146	1,282
Khorasan	686	1,394	660	2,288	5,028	663	28	692
Khuzestan	869	915	967	1,372	4,123	388	69	456
Kurdestan	116	136	56	201	509	1,593	135	1,728
Lorestan	220	218	107	351	897	785	101	886
Markazi	191	227	177	297	893	457	75	532
Qazvin	170	190	128	224	713	233	11	244
Tehran	212	242	203	297	954	6	0	7
Western Azerbaijan	292	232	112	318	954	751	43	794
Zanjan	64	64	45	91	263	986	167	1,152
Sum	5,107	6,244	4,679	9,026	25,055	10,158	1,145	11,303
AWF (m^3/ton)	690	844	632	1,220	3,385	2,663	300	2,963
WAWF (m^3/ton): National	1,328	571	525	825	3,249			
WAWF (m^3/ton): Global [1]	2,412	988	290	–	3,690			
NWF (MCM): National	17,222	7,406	6,809	10,706	42,143			
NWF (MCM): Global [1]	26,669	10,940	3,208	–	40,847			

[1] Mekonnen and Hoekstra (2010)

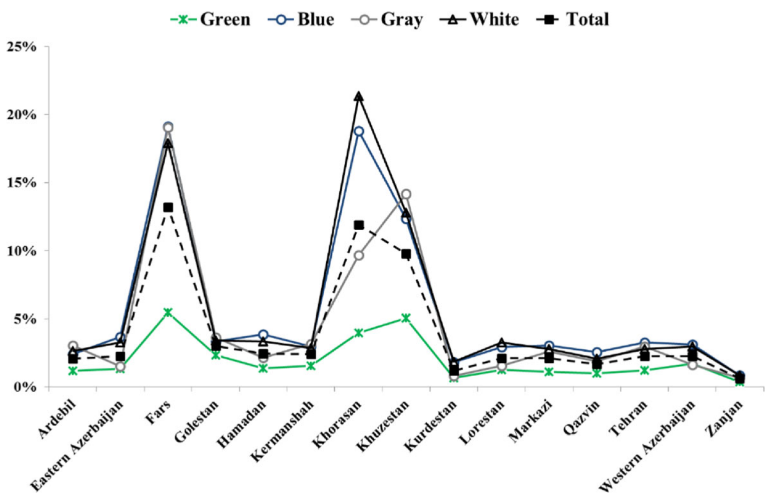

Fig. 3 The shares of the major wheat producing provinces from the national volumes of each WF components

estimates seem more accurate than those of Mekonnen and Hoekstra (2010). The coefficients of variations (CV) of ET_{c}., *IR* and P_{eff} between selected provinces are 13 %, 22 % and 13 %, respectively, which indicate considerable variations across the country and the need for using smaller assessment scales. With respect to the gray WF, Mekonnen and Hoekstra (2010) used a country-specific *NAR* value. Instead, the average values at a provincial scale obtained from AJM were used here. It is rational to consider the provincial data more accurate than the estimates at a national or global scale.

A variety of assumptions about input data and modeling of yield have an influence on the green WF estimate (Mekonnen and Hoekstra 2010). The blue WF estimate depends also on actual irrigation data. In regional studies, it is generally less time-consuming to find better estimates for various parameters than in national studies, and it is easier to validate the models for local conditions and reduce uncertainties.

5 Conclusions

A simplified approach was applied to estimate the white WF component. The rough estimates about maximum acceptable concentration of nitrogen in the receiving water bodies can be improved by using more sophisticated models. Results revealed that estimating WFs of crops at a global scale and estimating international virtual water flows based on those estimates, ignores the variations of climatic conditions, water resources availability and crop yields at the national and regional levels. Therefore, estimation of WF at the plain scale is proposed. This approach is able to determine where the WF of wheat production is originally located.

It was found that the green WF related to the national wheat production in Iran is about 2.3 times the blue WF, confirming the importance of green water in wheat production. Green water generally has a lower opportunity cost compared to blue water (Mekonnen and Hoekstra 2010). Since wheat has relatively low economic water productivity as compared to many other crops (Molden 2007), the question "to which extent should water be allocated to wheat production in a water-scarce basin?" must be answered. The relatively low yields in rainfed areas show that there are still opportunities to lower the green WF. Increasing production from rainfed areas will reduce the need for production from irrigated lands in water-scarce areas, and thus reduce blue water use. The gray WF in wheat production can generally be lowered substantially by precision farming, so that less fertilizers leach to groundwater or end to surface water through runoff (Jenkinson 2001; Norse 2005).

It was revealed that some of the assumptions made in previous global scale studies can lead to biased estimates of total volumes of wheat production water footprint. The authors admit that the accuracy of these results is subject to the quality of the input data. All similar studies suffer from the same sorts of limitations and handle these limitations in different ways. In future studies, it would be essential to study the sensitivity of the results to the initial assumptions and assessing the existing uncertainties in the final results.

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