AALTO UNIVERSITY
School of Engineering
Department of Civil and Environmental Engineering

Miina Porkka

The role of virtual water trade in physical water scarcity:

Case Central Asia

A master's thesis submitted for inspection for the degree of Master of Science in Technology

Espoo, August 29th 2011

Supervisor: Professor Olli Varis
Instructor: D.Sc. (Tech.) Matti Kummu

AALTO UNIVERSITY
SCHOOLS OF TECHNOLOGY
PO Box 11000, FI-00076 AALTO
http://www.aalto.fi

ABSTRACT OF THE MASTER’S THESIS

Author: Miina Porkka

Title: The role of virtual water trade in physical water scarcity: Case Central Asia

School: School of engineering

Department: Civil and environmental engineering

Professorship: Water resources engineering

Code: Yhd-12

Supervisor: Prof. Olli Varis

Instructor: D.Sc. (Tech.) Matti Kummu

Abstract:

Today’s globalised world is characterized by increased trade of water intensive products. The local and regional water scarcities should, therefore, also be examined in a global context. In this study the relation of physical water scarcity and virtual water trade in Central Asia was analysed. Two indices were used to identify water scarcity at the scale of sub-basin areas (SBAs): water stress index (i.e. consumption-to-availability ratio) and water shortage index (i.e. water availability per capita). Impact of virtual water trade on water scarcity was studied by calculating water scarcity indices for a baseline scenario that included virtual water flows, and comparing them to a scenario where virtual water trade was assumed not to exist. I found that water stress was the dominant type of water scarcity in Central Asia. Over 80 % of the total study area population lived in areas that suffered from water stress. About a half of the total population lived in areas that were also short of water resources. Most SBAs are net virtual water exporters, thus the impact of removing virtual water flows was mostly positive. The elimination of virtual water trade considerably decreased water scarcity for about a half of the total population. Inverting virtual water flows could thus be one solution for alleviating water scarcity in Central Asia, along with the more traditional measures of e.g. reducing water use intensity and increasing water use efficiency.

Date: 29.8.2011

Language: English

Number of pages: 31 + 5

Keywords: physical water scarcity, water stress, water shortage, virtual water trade, Central Asia

Aalto-yliopisto

AALTO-YLIOPISTO
TEKNIIKAN KORKEAKOULUT
PL 11000, 00076 AALTO
http://www.aalto.fi

DIPLOMITYÖN TIIVISTELMÄ

Tekijä: Miina Porkka

Työn nimi: Virtuaalivesivirtojen rooli veden fyysisessä niukkuudessa: Case Central Asia

Korkeakoulu: Insinööritieteiden korkeakoulu

Laitos: Yhdyskunta ja ympäristötekniikka

Professuuri: Vesitalous

Koodi: Yhd-12

Valvoja: Prof. Olli Varis

Ohjaaja: D.Sc. (Tech.) Matti Kummu

Tiivistelmä:

Tämän päivän globalisoituneessa maailmassa liikkuu kansainvälisen kaupan myötä suuria määriä paljon vettä kuluttavia maataloustuotteita. Paikallista ja alueellista veden niukkuutta pitäisikin siksi tarkastella globaalissa kontekstissa. Tässä tutkimuksessa analysoitiin veden fyysisen niukkuuden ja virtuaalivesivirtojen suhdetta Keski-Aasiassa. Veden niukkuutta tarkasteltiin osavaluma-alueiden (SBA:t) tasolla käyttäen kahta mittaria: vesistressi-indeksiä (veden käytön ja vesiresurssien suhde) sekä veden puutteen indeksiä (vesiresurssit väestöä kohden). Virtuaalivesivirtojen vaikutusta vesiniukkuuteen tutkittiin laskemalla indeksit perusskenaariolle, jossa virtuaalivesi oli otettu huomioon ja vertaamalla arvoja tilanteeseen, jossa virtuaalivesivirtojen oletettiin puuttuvan. Vesistressi oli Keski-Aasiassa dominoivampi vesiniukkuuden tyyppi. Yli 80% tutkimusalueen väestöstä asui vesistressistä kärsivillä alueilla. Noin puolet koko väestöstä asui alueilla joilla oli lisäksi puutetta vedestä. Suurimmalla osalla SBA-alueista virtuaaliveden vienti oli suurempaa kuin tuonti, joten virtuaalivesivirtojen poistamisen vaikutus oli pääosin positiivinen. Virtuaalivesivirtojen poistaminen vähensi vesiniukkuutta merkittävästi alueilla, jotka yhteensä asuttivat yli puolta koko tutkimusalueen väestöstä. Perinteisempien keinojen, kuten veden käytön tehostamisen, lisäksi virtuaalivesivirtojen kääntäminen nettoviennistä nettotuontiin voisikin olla yksi keino vähentää vesiniukkuutta Keski-Aasiassa.

Päivämäärä: 29.8.2011

Kieli: englanti

Sivumäärä: 31 + 5

Avainsanat: veden niukkuus, vesistressi, virtuaalivesivirrat, Keski-Aasia

Acknowledgements

This study was carried out at the Water & Development Research Group of Aalto University. The research was funded by Maa- ja vesitekniikan tuki ry and Academy of Finland project 133748.

I would like to thank all the people who have given me guidance during this process. I am extremely grateful to my instructor Matti Kummu for all the help he has offered me along the way, and to my supervisor Professor Olli Varis for his support and valuable comments. Special thanks goes to Stefan Siebert from University of Bonn and Martina Flörke from University of Kassel for providing me with data and their expertise when commenting the work.

Warm thank you to all the members of Water & Development Research Group for their encouragement and inspiration. I cannot imagine a better working environment. I would particularly like to thank Elina Heikinheimo who has been in the same boat with me throughout this process: thank you for your support and for setting me a deadline – it looks like we will make it to that plane after all.

Finally, I would like to thank all my friends and family for their support and understanding, and especially for offering me much needed distraction from writing this master's thesis.

Miina Porkka

Espoo, August 29th 2011

1 Introduction

Both population and fresh water resources are distributed very unevenly over the globe (e.g. Kummu & Varis, 2011) and water is considered a scarce resource in many regions (e.g. Ohlsson & Turton, 1999; Vörösmarty, 2000; Oki & Kanae, 2006; Alcamo *et al*, 2007). Water can be scarce either physically (Falkenmark *et al*, 1989) or socially, induced by political power, policies and/or socio-economic relations (e.g. Ohlsson & Turton, 1999). In this study I concentrate on physical water scarcity without, however, diminishing the importance of social water scarcity.

Physical water scarcity can be roughly divided into two main categories: population-driven water shortage and demand-driven water stress (Falkenmark *et al*, 2007). Population-driven water shortage occurs in areas where a large population has to depend on a limited resource while demand-driven water stress is related to the excessive use of otherwise sufficient water resources (Falkenmark *et al*, 2007).

It has been estimated that around one third of the world's population is living in areas that suffer from physical water scarcity, either from water shortage (Arnell, 2004; Alcamo *et al*, 2007; Islam *et al*, 2007; Kummu *et al*, 2010) and/or from water stress (Vörösmarty, 2000; Oki & Kanae, 2006; Alcamo *et al*, 2007). In today's globalised world, however, the importance of local water management has somewhat changed due to the rapidly increased trade of agricultural and other water intensive products. Therefore, many areas are not anymore depending solely on their local water resources but more and more on the combination of those with the global trade of virtual water. Global virtual water trade is approximately 1625 km^3/yr (Chapagain & Hoekstra, 2008), being about a half of the total blue water (surface and ground water) consumption (Oki & Kanae, 2006). Water scarcity is thus globalised and should be analysed in this context.

The relevance of virtual water flows depends largely on the location of exporting and importing areas. In some areas virtual water flows help to alleviate water scarcity, as water-intensive products are imported instead of producing them locally. There have been various global studies addressing water scarcity (e.g. Vörösmarty, 2000; Oki *et al*, 2001; Arnell, 2004; Alcamo *et al*, 2007; Kummu *et al*, 2010) and virtual water trade (e.g. Oki & Kanae, 2004; Chapagain & Hoekstra, 2008; Hanasaki *et al*, 2010) but only few that assess the implications of virtual water trade for water scarcity. Hoekstra and Hung (2005) quantified virtual water flows between countries and analysed national virtual water balances in relation to water needs and water availability. Kumar and Singh (2005) examined whether a relationship exists between the extent of virtual water trade and water availability in a country. Islam et al. (2007) did a grid-based assessment of water scarcity with virtual water trade included.

In addition to global studies, various case studies have addressed the connection of virtual water and water scarcity (e.g. Wichelns, 2001; Yang & Zehnder, 2001; Yang *et al*, 2007; Faramarzi *et al*, 2010). Studies suggest that some areas are so dependent on imported water that they simply could not sustain the population without it. Jordan, for example imports annually around 5-7 km^3 of water in virtual form – in sheer contrast with the country's domestic annual withdrawal of 1 km^3/yr (Chapagain & Hoekstra, 2008). However, limited domestic water resources are rarely the driving force behind virtual water trade (e.g. Wichelns, 2004). In some areas large exports of water extensive products can even be an important part of the reason behind water scarcity.

Central Asia is one of the regions that are virtual water exporters (Chapagain & Hoekstra, 2008; Hanasaki *et al*, 2010) despite their limited fresh water resources (e.g. Vörösmarty, 2000; Oki & Kanae, 2006). Although water is regionally relatively abundant there, its excessive use – particularly for irrigated agriculture – has led to severe local water deficits (Aldaya *et al*, 2010). This has partly been addressed by e.g. Aldaya et al. (2010) who calculate the water footprint of Central Asian cotton, wheat and rice. They did not, however, assess their implications for water scarcity. Although the Central Asian situation has been addressed in global studies, as addressed above, to my best knowledge the impact of virtual water trade on water scarcity has not been studied in detail.

In this study my objective is thus to analyse the relation of water scarcity and virtual water trade in Central Asia. The aim of this work is first, to assess the extent and severity of water scarcity in the region. Both water scarcity categories, i.e. water stress and water shortage, are analysed to understand the nature of the water scarcity in the region. Secondly, the aim is to assess the impact of virtual water trade on water scarcity in Central Asia. I estimate the virtual water flows of 71 crop and livestock commodities and calculate the combined water savings and losses. The analysis is carried out in the geographical scale of sub-basin areas (SBAs), a combination of large river basins, national borders and climate zones, to represent the unit in which water is normally managed (this can be compared to Food Production Units used in Kummu et al. (2010)).

2 Study area

The study area is defined by the borders of the six Central Asian countries: Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (Figure 1A). Region's water resources are dominated by Syr Darya and Amu Darya (Figure 1B), the two rivers feeding the Aral Sea. Together the river basins contribute to 38% of the surface area (Water Resources eAtlas, 2003) and 50% of the annual renewable water resources of the region (Alcamo *et al*, 2003a). They also hold 73% of the total population of the study area (Klein Goldewijk *et al*, 2010). Larger of the two rivers is Amu Darya, with a catchment area of 692,300 km^2 (O'Hara, 2000) and a mean annual runoff of 79.4 km^3 (Severskiy, 2004). With an annual runoff of 37.2 km^3, Syr Darya is considerably smaller than the Amu Darya (Severskiy, 2004).

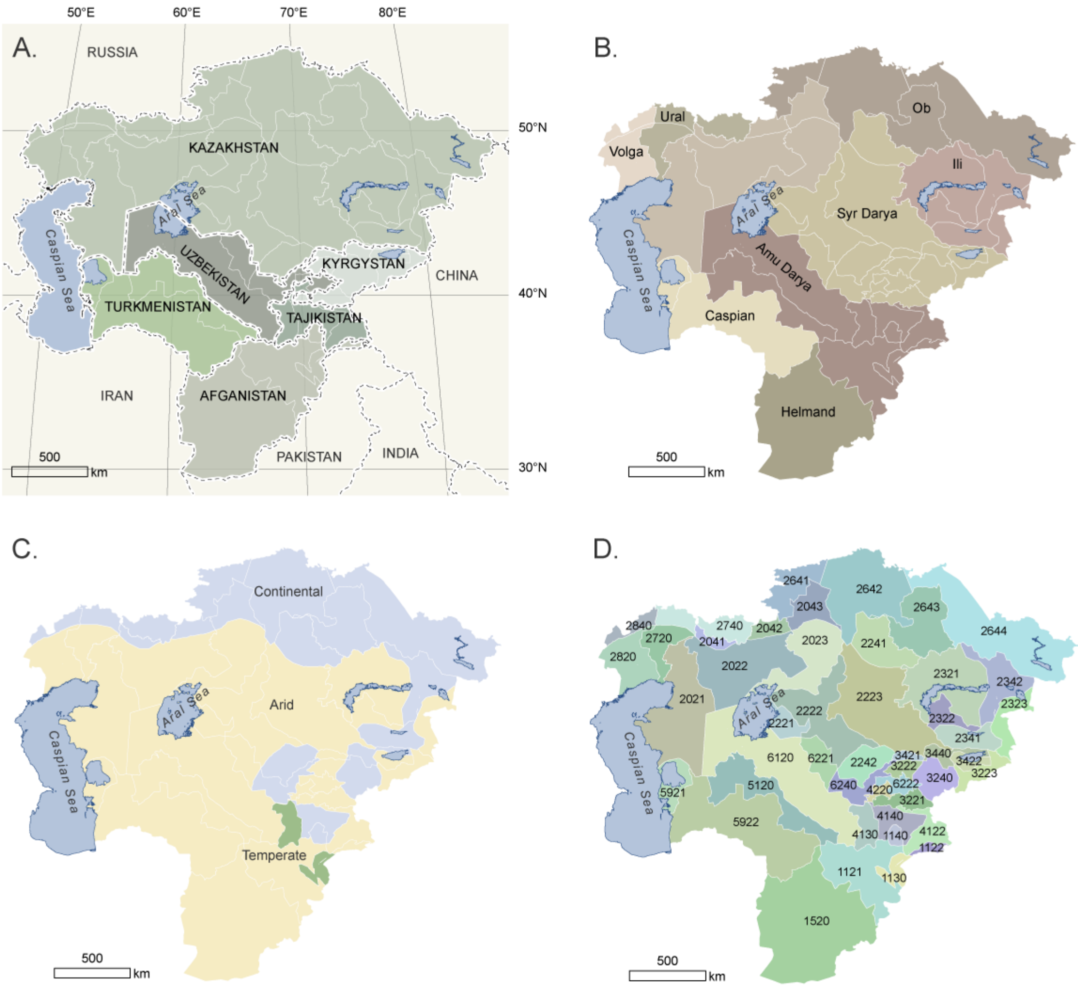


Figure 1. Study area division. A: National boundaries (USGS, 2001); B: Basin boundaries (Water Resources eAtlas, 2003); C: Climate zones (Rubel & Kottek, 2010); and D: Sub-basin areas (SBAs).

In the Amu Darya and Syr Darya basins, more than 65 % of water available for use is generated in the areas of Tajikistan and Kyrgyzstan, yet the biggest consumers are Uzbekistan and Turkmenistan (O'Hara, 2000). In these two countries, the national economies are largely based on irrigated agriculture, particularly cotton production (Aldaya *et al*, 2010). The countries are almost entirely dependent on water resources coming from transboundary rivers originating in upstream states (Severskiy, 2004).

Other major river basins inside the study area are the Ili basin in Kazakhstan and the Helmand basin in Afghanistan (Figure 1B). The area also includes portions of Ob, Ural and Volga river basins. A more detailed description of the large Central Asian river basins and their social, economic and environmental vulnerability can be found in Varis & Kummu (in press).

The study area is dominated by the arid climate, with some temperate patches in the east and continental climate belt in the north (Figure 1 C). Thus, large part of the region is naturally rather dry what comes to the available water resources. Annual precipitation ranges from about 100 mm in the dry lowlands to 500 mm in the high mountain areas of Tajikistan and Kyrgyzstan (Törnqvist & Jarsjö, 2011).

3 Materials and methods

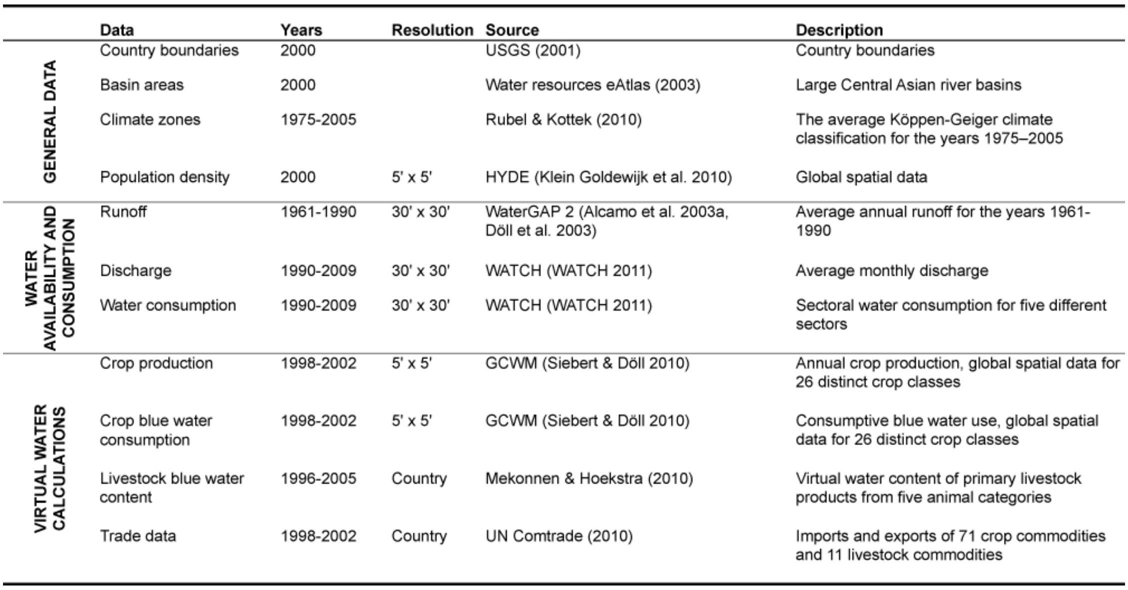
3.1 Spatial scale of analysis

The study area was divided into SBAs (sub-basin areas), based on large river basins (Figure 1B), climate zones (Figure 1C) and administrative regions (Figure 1A) (see Table 1 for data sources). This resulted altogether 47 SBAs (Figure 1D). Eight large basins were distinguished, namely Amu Darya, Syr Darya, Ili, Helmand, Ob, Ural, Volga and Caspian Sea. To simplify the division, some smaller areas outside these basins were merged into the closest large river basin. Basin areas from Ob, Volga and Ural that lie outside the six study countries were not included in the analyses. Later on, 'Other basin' in tables and figures refers to the SBAs that do not belong to any of the large river basins. While all the analyses were carried out at SBA scale, some results are also presented aggregated to basin and country levels. For comparison some results obtained from country and basin scale analyses are also presented in the 'Discussion' section.

3.2 Preparation of materials

In this section the preparation of the materials used for the analyses (see Table 1) is presented. The materials can be divided in four categories: population density, water resources availability, water consumption, and virtual water trade.

Table 1. Datasets used in the study.



	Data	Years	Resolution	Source	Description
GENERAL DATA	Country boundaries	2000		USGS (2001)	Country boundaries
	Basin areas	2000		Water resources eAtlas (2003)	Large Central Asian river basins
	Climate zones	1975-2005		Rubel & Kottek (2010)	The average Köppen-Geiger climate classification for the years 1975–2005
	Population density	2000	5' x 5'	HYDE (Klein Goldewijk et al. 2010)	Global spatial data
WATER AVAILABILITY AND CONSUMPTION	Runoff	1961-1990	30' x 30'	WaterGAP 2 (Alcamo et al. 2003a, Döll et al. 2003)	Average annual runoff for the years 1961-1990
	Discharge	1990-2009	30' x 30'	WATCH (WATCH 2011)	Average monthly discharge
	Water consumption	1990-2009	30' x 30'	WATCH (WATCH 2011)	Sectoral water consumption for five different sectors
VIRTUAL WATER CALCULATIONS	Crop production	1998-2002	5' x 5'	GCWM (Siebert & Döll 2010)	Annual crop production, global spatial data for 26 distinct crop classes
	Crop blue water consumption	1998-2002	5' x 5'	GCWM (Siebert & Döll 2010)	Consumptive blue water use, global spatial data for 26 distinct crop classes
	Livestock blue water content	1996-2005	Country	Mekonnen & Hoekstra (2010)	Virtual water content of primary livestock products from five animal categories
	Trade data	1998-2002	Country	UN Comtrade (2010)	Imports and exports of 71 crop commodities and 11 livestock commodities

3.2.1 Population density

Population density data were derived from the 5′ x 5′ resolution HYDE dataset (Klein Goldewijk *et al*, 2010) and aggregated to SBA scale (See figure 2A). The most densely populated SBAs are located in the upper Syr Darya and Amu Darya basins, which is where many of the biggest cities of Central Asia are situated. Vast areas of the region, especially Kazakhstan, are very sparsely populated.

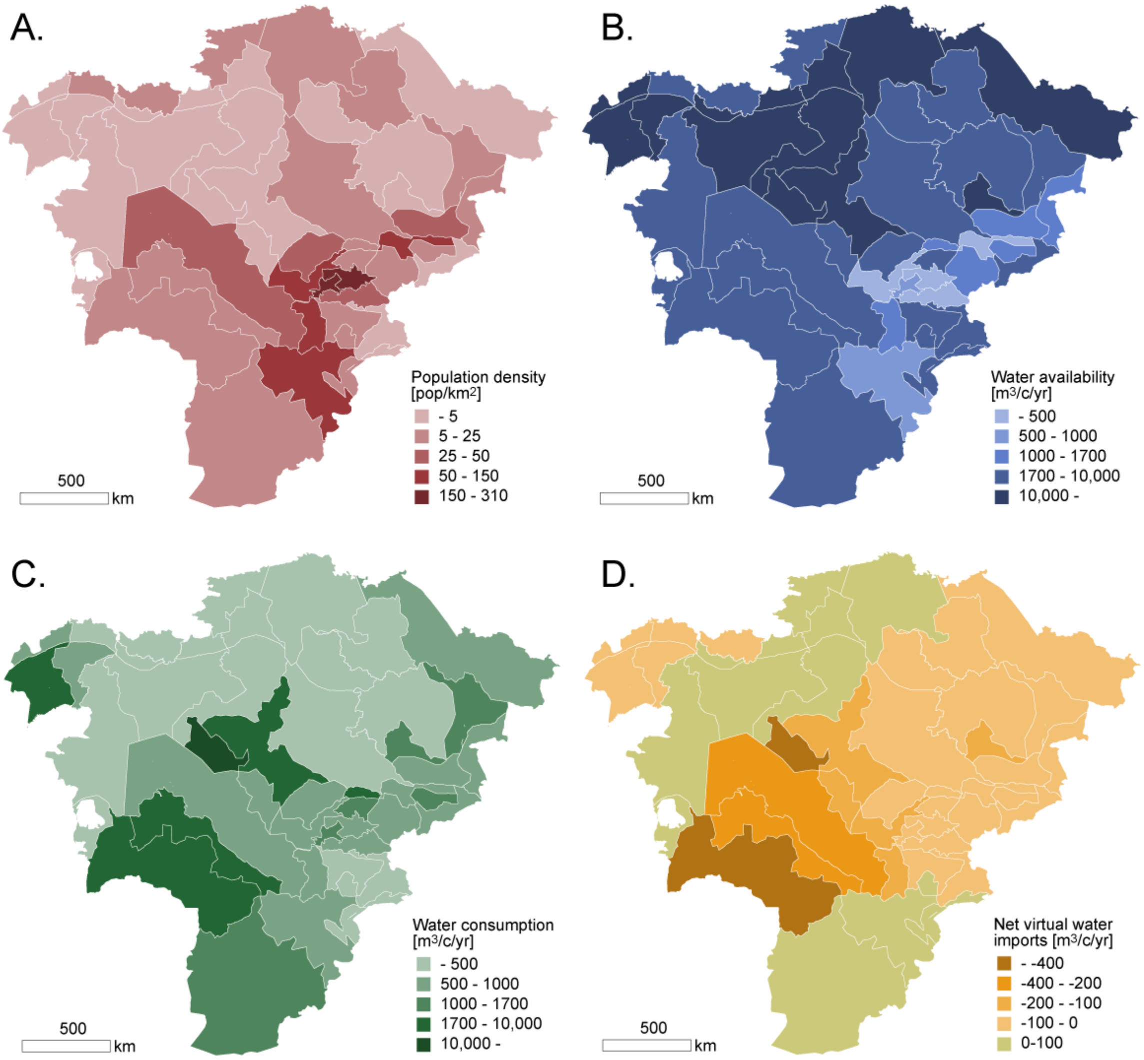


Figure 2. Maps of the materials. A: Population density; B: Water availability; C: Water consumption; D: Net virtual water imports.

3.2.2 Water resources availability

The available water resources were based on mean annual runoff with a spatial resolution of 30′ x 30′ from WaterGAP 2 model results (Alcamo *et al*, 2003a; Döll *et al*, 2003). In addition to this, cell level discharge data based on the global WATCH dataset with a similar spatial resolution (WATCH, 2011) was used. Average monthly discharges for 1990–2009 were used to calculate mean annual discharge for 2000.

Four indicators of water resources availability on SBA level were computed:

A. The equal sharing approach: runoff of the whole basin is distributed evenly for each grid cell inside the basin.
B. Local runoff approach: sum of cell specific runoff is computed for each SBA.
C. Upstream-to-downstream approach: method takes into account both the local runoff of the SBA and the water that originates from upstream. Here, it is assumed that all the resources that are not consumed in the upper SBA are available in the lower SBA. Flow routing between SBAs was done manually based on the actual river network.
D. Discharge proportion approach: the ratio of sum of SBA discharges to sum of basin discharges is used to divide the basin runoff between SBAs.

The equal sharing (A) is the simplest approach. It does, however, ignore the naturally irregular distribution of water resources inside a river basin and therefore is not very realistic. The local runoff (B) takes into account the irregularity inside a river basin but tends to give unrealistically low values for downstream areas where most of the available water resources originate from upstream. The upstream-to-downstream (C) gives perhaps the most realistic estimation of actual available water resources of a small area such as an SBA or a grid cell. Due to the accumulation of water in the downstream areas, the method is, however, not very suitable for aggregating the results from SBA scale to basin or country scale. Thus, I selected to use the discharge proportion approach (D) in the calculations. The approach is rather realistic, assuming a simple treaty how the water is managed in each transboundary river basin. In addition, the available water resources are not counted many times over the basin. The method does, however, often give lower values to some of the wet upstream parts of the basin compared to other approaches.

Although the SBA scale calculations are presented from the 'Discharge proportion' approach (see Figure 2B), the calculations were also carried out by using the other three approaches described above. As discussed in more detail in the 'Discussion' section, it should be noted also here, that in certain SBAs the choice of method for calculating water availability has a significant impact on water scarcity calculations.

Table2. Materials used in the analyses. SBA scale numbers are presented in Annex 1.

Basin	Population ($x10^6$)	Available water resources (km^3/yr)	Per capita water resources ($km^3/c/yr$)	Water consumption (km^3/yr)						Net virtual water imports (km^3/yr)
				Irrigation	Livestock	Electricity	Manufacturing	Domestic	Total	
Amu Darya	31.3	65.3	2087.0	22.7	0.1	0.0	0.4	0.7	24.0	-5.0
Syr Darya	23.9	41.7	1744.2	15.7	0.1	0.0	0.4	0.9	17.2	-1.9
Ili	3.2	12.4	3874.8	2.0	0.0	0.0	0.1	0.2	2.3	-0.1
Helmand	7.4	14.0	1891.9	9.8	0.0	0.0	0.0	0.1	9.9	0.1
Ob	5.0	50.9	10172.2	0.9	0.1	0.1	0.1	0.3	1.5	0.0
Ural	1.1	4.6	4190.2	0.3	0.0	0.0	0.0	0.1	0.4	0.0
Volga	0.2	2.5	12574.1	0.2	0.0	0.0	0.0	0.0	0.3	0.0
Caspian Sea	2.4	8.1	3373.7	4.3	0.0	0.0	0.0	0.1	4.4	-1.1
Other basin	0.9	13.8	15365.3	0.0	0.0	0.0	0.0	0.1	0.1	0.0
Total	**75.4**	**213.3**	**2829.2**	**56.0**	**0.5**	**0.2**	**1.0**	**2.5**	**60.1**	**-7.9**

Groundwater resources are relatively easily accessible in many parts of the study area. Their quality is, however, reported to be significantly lower than that of surface water, especially in many downstream areas (Törnqvist & Jarsjö, 2011). Moreover, accurate data for groundwater resources is not easily available, thus only surface waters were included in this study. It should also be noted that water quality issues, such as salinity and contamination, which have a rather big impact on water usability in Central Asia (Severskiy, 2004), have not been considered in this study.

3.2.3 *Water consumption*

Sectoral water consumption data were derived from the global 30′ x 30′ resolution WATCH dataset (WATCH, 2011) with five sectors, namely irrigation, domestic, manufacturing, electricity and livestock. Average annual water consumption data for 1990-2009 were used to calculate sectoral water consumption for the year 2000. Values were then aggregated to SBA scale. Water consumption for each sector is presented in Table 2 and the totals mapped in Figure 2C. According to the calculations, agriculture is the dominant water user, accounting for 93% of total water consumption in the study area. Next largest are domestic and manufacturing sectors, which make up 4% and 2% of total water consumption respectively. Livestock and electricity water consumption constitute the remaining one per cent of the Central Asian total.

3.2.4 Virtual water calculations

Global crop water model GCWM (Siebert & Döll, 2010) was used to calculate the virtual water content of crops and crop products. Output of the model has a spatial resolution of 5′ x 5′, distinguishing consumptive blue (evaporation of irrigation water) and green water use (evapotranspiration of infiltrated rainwater) for 26 different crop classes, of which 23 were included in this study (see Annex II). Crop specific production (kg/yr) and blue water consumption (m^3/yr) data were aggregated to SBA scale and used to calculate the crop specific virtual water content (m^3/kg) in each SBA.

For livestock water consumption, results of Mekonnen & Hoekstra (2010) were used. In this global study they estimated the green, blue and grey virtual water content of farm animals and the derived animal products for the period 1996–2005. Three different production systems were distinguished, and based on a spatially explicit crop water use model and estimates of the amount and composition of feed in each system, virtual water content of livestock products were calculated at country level. I used the estimates of virtual water content of five primary livestock products, namely raw milk and live bovine, swine, sheep and fowls, in further calculations.

Country scale import and export data of 71 crop commodities and 11 livestock commodities (see Annex 2) for years 1998–2002 were obtained from the Comtrade database of the United Nations (UN Comtrade, 2010). Only the most important commodities were included in the study. It was assumed that the production of possible by-products of these commodities (e.g. oil-cake from extraction of sunflower seeds for sunflower oil) does not increase the production of the primary product (e.g. sunflower) and thus does not affect the virtual water content of commodities (e.g. sunflower oil). Average weight of annual imports and exports of each commodity were converted to the equivalent amount of the primary product according to specific extraction rates (amount of processed product obtained from processing the primary product). Extraction rates were estimated based on commodity trees by FAO (2003). In the case of cotton products, estimations by Chapagain et al. (2006b) were used.

National exports of crop products were divided between SBAs in proportion to the production of each crop class. In the case of exporting livestock products, the proportion of livestock water consumption was used to represent the spatial distribution of livestock production inside a country. National imports of crop and livestock products were distributed between SBAs in proportion to their total population. Finally, to obtain the SBA scale virtual water flows (see Figure 2D), trade flows of each SBA were multiplied with their respective crop and livestock product specific virtual water content unique to that particular SBA. In the case of imports, virtual water content characteristic to the importing SBA was used rather than water actually consumed in the place of production. This enables to quantify the water savings induced by virtual water imports in Central Asia. Due to the lack of information on internal trade, virtual water flows inside a nation were not taken into account.

Both GCWM (Siebert & Döll, 2010) and Mekonnen & Hoekstra (2010) distinguish between blue and green crop water consumption. However, green water scarcity is quite difficult to define and further research is required to identify the thresholds at which an area faces green water scarcity (Rockström *et al*, 2009). Therefore I chose to only analyse blue water scarcity and the blue fraction of virtual water trade in this study, while not forgetting the importance of green water in crop production and food security. Green water also has an important role in water savings through virtual water trade. In many arid and semi-arid areas, such as Central Asia, imports of green water replace the local blue water resources that would be needed to produce agricultural products domestically. However, despite excluding green water from the analysis, these savings of blue water have been taken into account by using the importing area's virtual water content in the calculations, as described above.

An example of estimating the virtual water flows related to trade of cotton products in Uzbekistan is presented in Annex 3.

3.3 Methods

3.3.1 Water scarcity

Two indices for physical water scarcity were used in this study: the water crowding index (WCI), i.e. Falkenmark's index (Falkenmark, 1997), and the water stress index (WSI). WCI was used to measure population-driven water shortage and is defined here as the annual available water resources per capita. Demand-driven water stress is usually measured with the ratio of water withdrawals to available water resources (e.g. Falkenmark, 1997; Vörösmarty, 2000). In this study I decided to use the ratio of annual water consumption to available water resources for calculating WSI. I believe, that using water consumption rather than withdrawals is more appropriate for the Central Asian conditions because of the reported importance of downstream reuse of return flows of irrigation water withdrawn in upstream areas (Törnqvist & Jarsjö, 2011; Aus der Beek *et al*, 2011). Water scarcity refers here to both water shortage and water stress.

I follow the thresholds and definitions of different levels of water scarcity defined by Falkenmark et al (2007):

- WCI:
    - Moderate water shortage: per capita water availability is 1000–1700 m^3/yr.
    - Chronic water shortage: per capita water availability is < 1000 m^3/yr.
- WSI:
    - Moderate water stress: consumption of 20–40 % of available water resources.
    - High water stress: consumption of over 40 % of available water resources.

It should be noted that I used the water stress thresholds defined for withdrawals-to-availability ratio because such thresholds for consumption-to-availability ratio have not been defined. Moreover, it was assumed that the thresholds used in this study are fixed and do not change over time or based on the location, even though there are processes (e.g. technological change, structural change etc.) that may have an impact on currently used thresholds.

Both indices were calculated for each SBA based on the materials described above. Although water scarcity assessments normally use only one indicator to describe the level of water scarcity (e.g. Oki *et al*, 2001; Alcamo *et al*, 2003b; Arnell, 2004; Islam *et al*, 2007; Kummu *et al*, 2010), I believe that the use of both WCI and WSI in parallel gives a better understanding of the nature of water scarcity and the reasons behind it. Furthermore, both indices have their limitations, as discussed in Rijsberman (2005), and using the two together is likely to give a more valid estimate of the extent of water scarcity in Central Asia. The results are presented in a water scarcity matrix developed by Falkenmark (1997) (Figure 3). The matrix is a plot of WCI (horizontal scale) and WSI (vertical scale). It distinguishes moderate and chronic water shortage, moderate and high water stress, and the combinations of different levels of the two water scarcity indices. Water scarcity categories are presented in Figure 3, along with the principal drivers that lead to changes in the indices.

3.3.2 Impact of virtual water trade on water scarcity

Water scarcity indices were first calculated for the baseline scenario, where virtual water trade was included. When calculating the WCI index for each SBA, virtual water flows were included in the calculations by treating them as natural flows entering or exiting the area. In the baseline scenario net virtual water exports were subtracted from the exporting

SBAs available water resources. Likewise, net virtual water imports were added to the importing area's natural water resources. In the second scenario, where virtual water flows were eliminated, only the locally available water resources were used to calculate WCI. This increases the WCI value in net exporting areas and decreases it in net importing areas compared to the baseline (Figure 3).

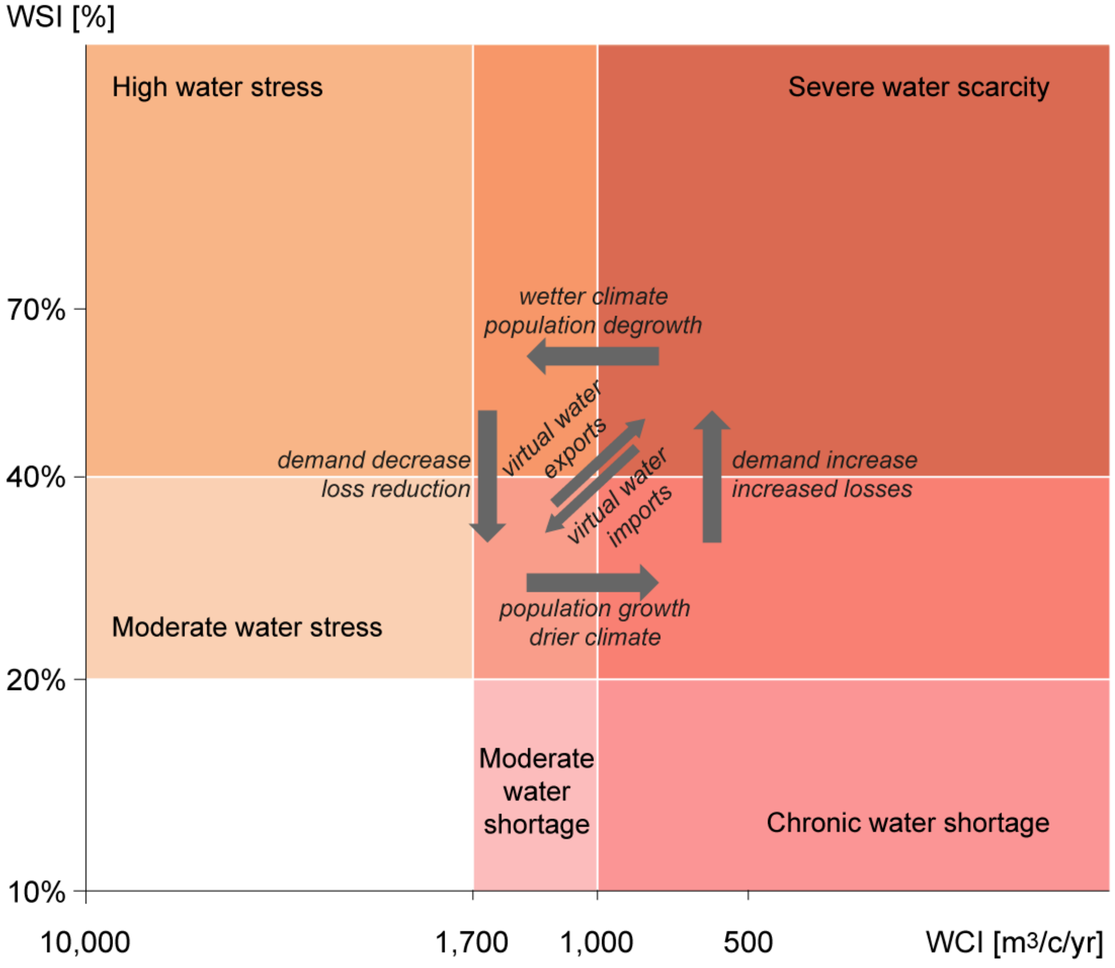


Figure 3. Water scarcity categories and their thresholds. Arrows indicate the effect of the principal drivers of change.

WSI for the baseline scenario was calculated by dividing consumptive water use with locally available water resources. In the second scenario, virtual water trade was eliminated by adding net virtual water imports to the importers' water consumption, which increases the WSI value (Figure 3). This represents the additional water needed to produce the formerly imported commodities domestically. Similarly, net virtual water exports were subtracted from the exporters water consumption, which represents the water savings when the formerly exported commodities are not produced. These water savings decrease the WSI value compared to the baseline scenario (Figure 3).

4 Results

4.1 Water scarcity

Demand-driven water stress was the dominant type of water scarcity in Central Asia. Most SBAs had sufficient water resources in relation to their population, and all the areas that experienced some form of water scarcity suffered from either water stress alone (high WSI value) or both water stress and water shortage (high WSI and low WCI value) (Figure 4a). The few areas where population-driven water shortage occurred along with water stress, however, hold almost a half (37.4 million) of the total population of the study area. Thus, water shortage is also significant in Central Asia, despite the seemingly plentiful per capita water resources (Table 2).

According to the calculations 84% (63.6 million) of the study area population lived under some level of water scarcity. About a half of them lived in areas that suffered from severe water scarcity in the sense that both high water stress and chronic water shortage occurred (Figure 4a, Table 3). 65% of the population experienced high water stress, with majority of them living in areas with less than 1700 m^3 of water per capita per year.

Water scarcity occurred mainly in Amu Darya, Syr Darya, Ili, Helmand and Caspian Sea basins, where it affected over 75% of each basin's population (Figure 4a, Table 3). Scarcity was particularly serious in Amu Darya and Syr Darya basins, where 40% and 75% of population respectively was classified as being under severe water scarcity (Table 3). In Syr Darya basin, all of this population lived under extreme water shortage with a WCI value of less than 500 m^3/capita/yr. In Ili and Syr Darya basins, scarcity occurred only in the upstream end, whereas in other water scarce basins the downstream end was also affected (Figure 5a). When water scarcity was examined on country scale, Afghanistan, Kyrgyzstan and Uzbekistan stood out particularly, with over half of the population (61%, 67% and 52% respectively) living under severe water scarcity (Table 3).

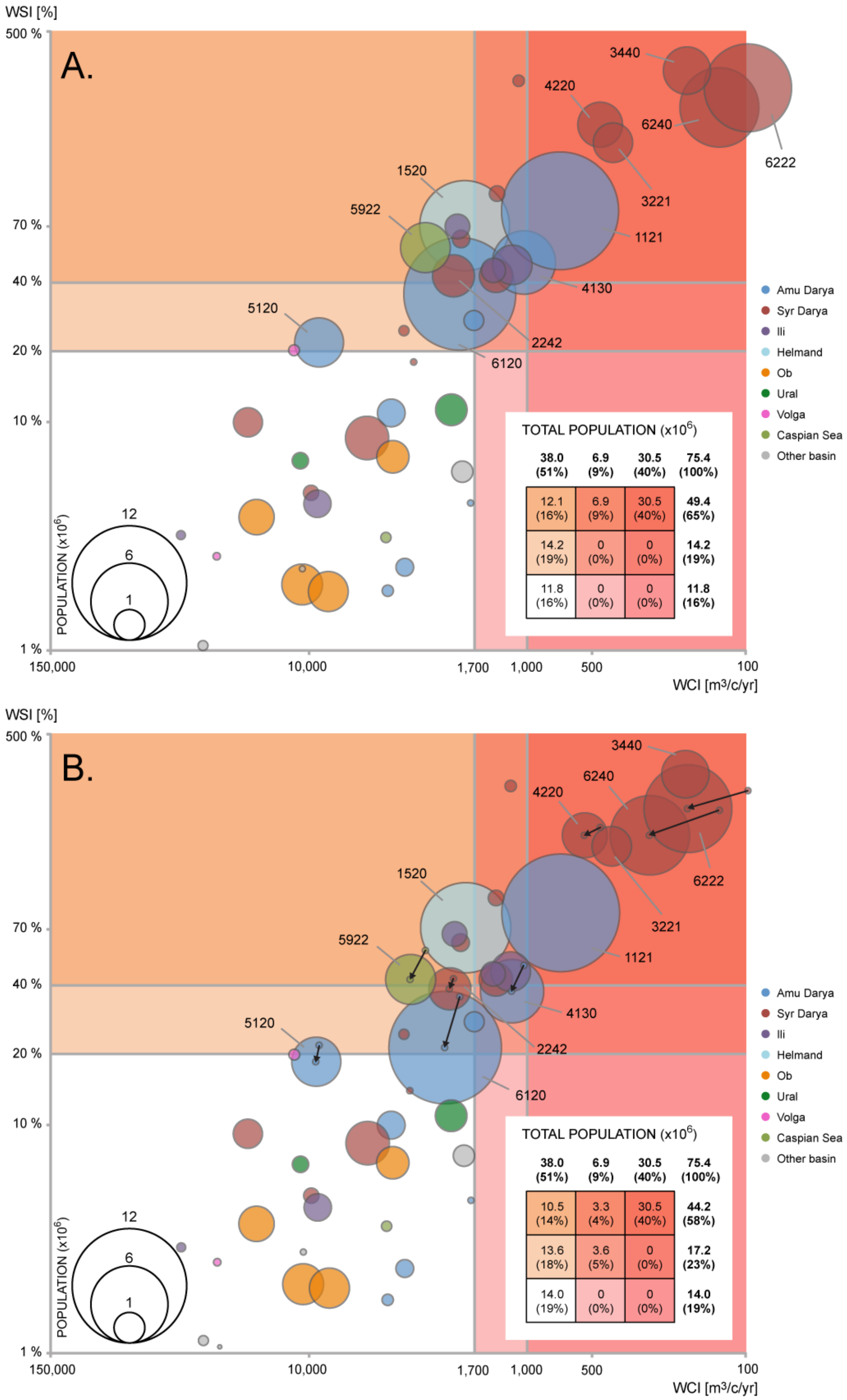


Figure 4. Water scarcity results in matrix plot. A: Baseline scenario; and B: Scenario without virtual water trade. Bubble sizes indicate the population of the SBAs and colours the river basin they belong to. Total population in each of the matrix's nine areas is presented in the lower right corner of A and B, with the percentage of total Central Asian population in brackets. Arrows in B mark the change due to eliminating virtual water trade. Both axes have a logarithmic scale.

Table 3. Results of population under different water scarcity categories aggregated to basin and country levels, baseline scenario on the left and scenario without virtual water trade on the right. Note: categories that do not appear in the table equal to 0. See Annex 4 for SBA scale results.

		Baseline scenario						**Scenario without virtual water**						
			Population under water scarcity (x10^6)						Population under water scarcity (x10^6)					
	Population (x10^6)	Population not under water scarcity (x10^6)	Moderate water stress (MWS)	High water stress (HWS)	HWS + moderate water shortage	Severe water scarcity	Total under water scarcity	Population not under water scarcity (x10^6)	Moderate water stress (MWS)	High water stress (HWS)	MWS + moderate water shortage	HWS + moderate water shortage	Severe water scarcity	Total under water scarcity
Basin														
Amu Darya	31.3	1.1 (4%)	14.0 (45%)	0	3.6 (12%)	12.5 (40%)	30.1 (96%)	3.3 (11%)	11.8 (38%)	0	3.6 (12%)	0	12.5 (40%)	28.0 (89%)
Syr Darya	23.9	2.7 (11%)	0.1 (0%)	1.9 (8%)	1.3 (6%)	17.9 (75%)	21.2 (89%)	2.7 (11%)	1.7 (7%)	0.3 (1%)	0	1.3 (6%)	17.9 (75%)	21.2 (89%)
Ili	3.2	0.7 (23%)	0	0.6 (17%)	1.9 (60%)	0	2.5 (77%)	0.7 (23%)	0	0.6 (17%)	0	1.9 (60%)	0	2.5 (77%)
Helmand	7.4	0	0	7.4 (100%)	0	0	7.4 (100%)	0	0	7.4 (100%)	0	0	0	7.4 (100%)
Ob	5.0	5.0 (100%)	0	0	0	0	0	5.0 (100%)	0	0	0	0	0	0
Ural	1.1	1.1 (100%)	0	0	0	0	0	1.1 (100%)	0	0	0	0	0	0
Volga	0.2	0.0 (31%)	0.1 (69%)	0	0	0	0.1 (69%)	0.0 (31%)	0.1 (69%)	0	0	0	0	0.1 (69%)
Caspian Sea	2.4	0.1 (4%)	0	2.3 (96%)	0	0	2.3 (96%)	0.1 (4%)	0	2.3 (96%)	0	0	0	2.3 (96%)
Other basin	0.9	0.9 (100%)	0	0	0	0	0	0.9 (100%)	0	0	0	0	0	0
Total	**75.4**	**11.8 (16%)**	**14.2 (19%)**	**12.1 (16%)**	**6.9 (9%)**	**30.5 (40%)**	**63.6 (84%)**	**14.0 (19%)**	**13.6 (18%)**	**10.5 (14%)**	**3.6 (5%)**	**3.3 (4%)**	**30.5 (40%)**	**61.4 (81%)**
Country														
Afghanistan	20.6	0.3 (2%)	0.4 (2%)	7.4 (36%)	0	12.5 (61%)	20.3 (98%)	0.3 (2%)	0.4 (2%)	7.4 (36%)	0	0	12.5 (61%)	20.3 (98%)
Kazakhstan	14.7	10.5 (71%)	0.1 (1%)	2.2 (15%)	1.9 (13%)	0	4.2 (29%)	10.5 (71%)	1.7 (12%)	0.6 (4%)	0	1.9 (13%)	0	4.2 (29%)
Kyrgyzstan	5.1	0	0.1 (2%)	0.3 (5%)	1.3 (26%)	3.4 (67%)	5.1 (100%)	0	0.1 (2%)	0.3 (5%)	0	1.3 (26%)	3.4 (67%)	5.1 (100%)
Tajikistan	6.3	0.8 (13%)	0	0	3.6 (58%)	1.8 (29%)	5.5 (87%)	0.8 (13%)	0	0	3.6 (58%)	0	1.8 (29%)	5.5 (87%)
Turkmenistan	4.5	0.1 (2%)	2.2 (48%)	2.3 (50%)	0	0	4.4 (98%)	2.3 (50%)	0	2.3 (50%)	0	0	0	2.3 (50%)
Uzbekistan	24.1	0	11.4 (47%)	0	0	12.7 (52%)	24.1 (100%)	0	11.4 (47%)	0	0	0	12.7 (52%)	24.1 (100%)
Total	**75.4**	**11.8 (16%)**	**14.2 (19%)**	**12.1 (16%)**	**6.9 (9%)**	**30.5 (40%)**	**63.6 (84%)**	**14.0 (19%)**	**13.6 (18%)**	**10.5 (14%)**	**3.6 (5%)**	**3.3 (4%)**	**30.5 (40%)**	**61.4 (81%)**

4.2 *Impact of virtual water trade on water scarcity*

Most SBAs were net virtual water exporters (Figure 2D) and therefore the elimination of virtual water flows had generally a positive impact on water scarcity. In the net importing SBAs, virtual water flows were relatively small and thus their elimination did not increase the areas' water scarcity considerably. The combined virtual water flows of the eight largest net exporters (see Figure 4B), however, accounted for 99% of the whole Central Asia's net exports. These were all SBAs that suffered from some level of water scarcity.

Three of the eight large net exporters (2242, 4130 and 5120) were SBAs where the elimination of virtual water flows had an impact on water scarcity classification (Figure 4, Figure 5). In SBA 5120 water scarcity did not occur at all when virtual water flows were eliminated, while the other two moved to a less critical water scarcity category. There were significant changes also in other large net exporting SBAs. Three Uzbek SBAs in the Amu Darya and Syr Darya basins (6120, 6222 and 6240), one Tajik SBA in the Syr Darya basin (4220) and one Turkmen SBA in the Caspian Sea basin (5922) exported virtually over 14% of their available water resources. Elimination of virtual water flows alleviated water scarcity considerably in these eight areas that together hold 47% (35.6 million) of the total population of Central Asia (Figure 4B).

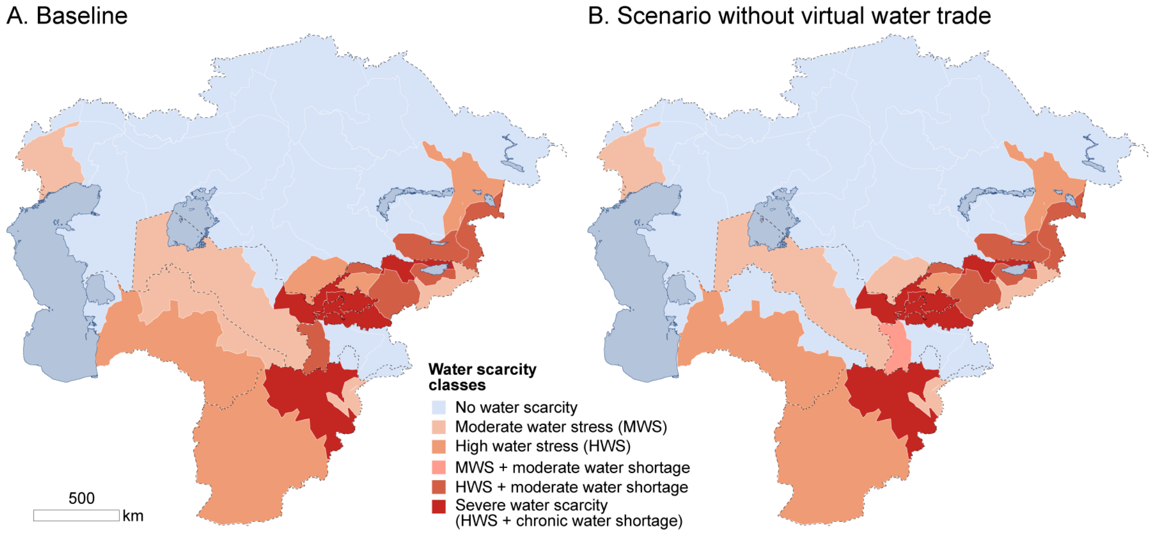


Figure 5. Water scarcity mapped for each SBA. A: Baseline scenario; and B: Scenario without virtual water trade.

5 Discussion

The results showed that over 80% of the total Central Asian population lived under some level of water scarcity. All of these people suffered from demand-driven water stress and about a half of them also from population-driven water shortage. This indicates that the main cause of water scarcity in the study area is over-exploitation of available water resources, which is mostly due to irrigated agriculture, as presented in Table 2. The GCWM model output (Siebert & Döll, 2010) shows that the production of cotton, wheat and rice accounts for 86% of the total agricultural blue water consumption in Central Asia. The proportion of cotton alone is 62%, making it the dominant cause of high agricultural water withdrawals. There is also a notable spatial overlap between cotton producing areas and areas that suffer from water stress, which suggests that they are indeed connected.

5.1 Virtual water trade: solution to water scarcity?

When assessing the number of people living under water scarcity, the elimination of virtual water flows did not have a very significant impact. Likewise, when assessing the number of SBAs affected by virtual water trade, notable changes in water scarcity indices could only be seen in eight of the 47 SBAs. However, in these SBAs the elimination of virtual water trade considerably decreased water scarcity. As these areas hold almost a half of the total population of Central Asia, the impact of virtual water trade on water scarcity can be considered significant both in SBA scale as well as regional scale.

Various measures to decrease water scarcity exist (e.g. Oki & Kanae, 2006; Falkenmark *et al*, 2007; Kummu *et al*, 2010). For demand-driven water stress, the most straightforward ways are related to reducing water use (Figure 3). In Central Asia, a shift from the water-hungry cotton to for instance grains could well decrease water demand in the most stressed areas (Aus der Beek *et al*, 2011). Grain production has indeed become more important in the region since the former Soviet Union states became independent in 1991, and cotton producing areas have decreased some over the past ten years (Aldaya *et al*, 2010; Aus der Beek *et al*, 2011). However, cotton – the main cash crop of the region – remains economically very important, particularly in the largest producing countries, Uzbekistan, Turkmenistan and Tajikistan (Aldaya *et al*, 2010). Thus, further transition away from cotton is likely to be very slow if it will occur at all. Another way to reduce water consumption to some extent would be to cut losses in water supply and irrigation systems. Improving the decayed Soviet-era infrastructure that is still widely in use in Central Asia could increase water use efficiency substantially (Severskiy, 2004). Törnqvist and Jarsjö (2011) found that an implementation of improved irrigation techniques in the Amu Darya and Syr Darya basins would lead to water savings that increase the discharge to the Aral Sea considerably.

While measures to combat demand-driven water stress can be fairly easy to take, simple solutions to alleviate population-driven water shortage are much more difficult to find. In the future, climate change could bring along wetter climate, which would increase water availability. However, while some projections do suggest increased runoff for certain parts of the study area (Vörösmarty, 2000; Arnell, 2004) population is also projected to grow (Varis & Kummu, in press). This is likely to decrease per capita water availability despite the possible wetter climate conditions (Arnell, 2004).

It has also been suggested that virtual water trade could decrease the pressure on domestic water resources in water scarce areas (e.g. Allan, 1998; Hoekstra, 2011). The idea applies to both population-driven and demand-driven scarcity: virtually imported water can be seen as an alternative water source along with domestic water resources, increasing the area's per capita water availability. On the other hand, if for example cereal crops – and the embedded virtual water – are imported instead of producing them domestically, less domestic water resources have to be used, decreasing the level of exploitation. Chapagain et al. (2006a) demonstrated that Morocco, for example, is saving 27 km^3/yr of its scarce domestic water resources through international trade of agricultural products. According to a global study by Islam et al. (2007), some 200-300 million people less fall into the chronic water shortage category if virtual water flows are taken into account. I found that most water scarce areas in Central Asia are currently net virtual water exporters. Inverting their virtual water flows from export to import would relieve pressure on the areas' water resources to a certain degree.

While the idea of water saving through international trade of agricultural products is appealing, in practice water scarcity is rarely the dominant factor behind virtual water trade. Other important factors, such as availability of land and labour often pay a decisive role in global trade patterns (e.g. Wichelns, 2004; Chapagain *et al*, 2006a; Ansink, 2010), which partly explains why many water scarce areas of the world are net virtual water exporters (Kumar & Singh, 2005; Chapagain & Hoekstra, 2008). These factors, as well as economical and political issues, have not been included in this study. It is safe to say that from a water resources point of view, decreasing the exports and increasing the imports of agricultural products would improve the situation in water scarce areas of Central Asia. Whether or not it would be beneficial in broader context, however, depends on other factors, such as resource endowments and production technologies in the countries encaging in trade. The question would, therefore, require further research.

5.2 Future research needs

As discussed briefly in 'Materials and methods' - section, the approach for calculating SBA scale water availability has a significant impact on the results of the analyses. I compared four different approaches to calculate WSI and WCI values for each SBA. Table 4 presents total Central Asian population under different water scarcity categories using the four approaches.

Population under some level of water scarcity was almost the same using discharge proportion, local runoff and equal sharing approaches, although there were considerable differences in some of the water scarcity categories (Table 4). Upstream-to-downstream approach gave significantly smaller values in most categories. With this approach the total population under some level of water scarcity was 67%, compared to around 85% using the other three approaches.

Another factor influencing the results is the spatial scale of the analyses. Table 5 presents the SBA, basin and country scale results of population under different water scarcity categories. Although the proportion of people under some level of water scarcity was very similar regardless of the scale, considerable differences could be seen in the most extreme categories (Table 5).

The variation in the outcomes of different approaches shows that it is important to acknowledge the influence of methodological

Table 4. Population under different water scarcity categories using alternative water availability approaches. Note: categories that do not appear in the table equal to 0.

		Population under water scarcity, baseline scenario ($x10^6$)						
Water availability approach	Population not under water scarcity ($x10^6$)	Moderate water stress (MWS)	High water stress (HWS)	MWS + moderate water shortage	HWS + moderate water shortage	Chronic water shortage	Severe water scarcity	Total under water scarcity
Equal sharing (A)	11.5 (15%)	17.1 (23%)	9.7 (13%)	0 (0%)	17.0 (22%)	0 (0%)	20.1 (27%)	63.9 (85%)
Local runoff (B)	12.1 (16%)	3.9 (5%)	13.7 (18%)	12.5 (17%)	12.9 (17%)	0.1 (0%)	20.1 (27%)	63.3 (84%)
Upstream-to-downstream (C)	24.9 (33%)	24.0 (32%)	11.8 (16%)	0 (0%)	0 (0%)	0.1 (0%)	14.7 (19%)	50.5 (67%)
Discharge proportion (D)	11.8 (16%)	14.2 (19%)	12.1 (16%)	0 (0%)	6.9 (9%)	0 (0%)	30.5 (40%)	63.6 (84%)

Table 5. Population under different water availability categories calculated at SBA, basin and country scale. Note: categories that do not appear in the table equal to 0.

Spatial scale of analyses	Population not under water scarcity (x10^6)	Population under water scarcity, baseline scenario (x10^6)				
		Moderate water stress	High water stress (HWS)	HWS + moderate water shortage	Severe water scarcity	Total under water sarcity
SBA	11.8 (16%)	14.2 (19%)	12.1 (16%)	6.9 (9%)	30.5 (40%)	63.6 (84%)
Basin	10.4 (14%)	31.3 (41%)	9.7 (13%)	23.9 (32%)	0 (0%)	64.9 (86%)
Country	14.7 (20%)	4.5 (6%)	0 (0%)	51 (68%)	5.1 (7%)	60.7 (80%)

choices on the results. This is overlooked in many of the water scarcity studies, and would require more global scale analysis. It should also be noted that universally accepted definition for water scarcity does not exist, thus more research is needed to clarify the concept and its classification. Moreover, groundwater resources and water quality concerns have an impact on the region's water scarcity. Especially in many downstream areas contamination and salinity reduce the volume of usable water resources (Severskiy, 2004; Törnqvist & Jarsjö, 2011). These issues should, therefore, be considered in future water scarcity analyses.

For a more accurate virtual water trade analysis and a better understanding of its impacts on water scarcity, an estimation of inter-country trade should be included in similar studies in the future. Inclusion of green water would also be an interesting addition to the current analyses. Furthermore, both physical water scarcity and global trade of agricultural products have developed greatly over the past decades, as demonstrated by Kummu et al. (2010). A regional historical analysis of water scarcity and virtual water flows could thus reveal interesting trends and give a better understanding of the connection between water scarcity and virtual water trade in Central Asia.

6 Conclusions

In this study I assessed the extent and nature of physical water scarcity in Central Asia at the scale of sub-basin areas (SBAs) by using two different indicators for water scarcity, namely water crowing index (water availability per capita) and water stress index (consumption-to-availability ratio). Further, I estimated the net virtual water flows for each SBA to analyse the impact of virtual water trade on water scarcity in the study area.

I found that demand-driven water stress was the dominant type of water scarcity in Central Asia. Large majority (84%) of the total population (75.4 million) lived in areas that suffered from demand-driven water stress and around a half in areas that also suffered from population-driven water shortage. Alarmingly, 40% of the population lived under severe water scarcity (over 40% of available water resources are consumed and per capita water availability is less than 1000 m^3/yr). Scarcity was the most widespread in Amu Darya and Syr Darya river basins.

The impact of virtual water trade on water scarcity was considerable in eight of the 47 SBAs. The affected SBAs were net virtual water exporters and suffered from water scarcity. Thus, in these areas the elimination of virtual water trade alleviated the serious situation significantly. Almost a half of the total population of Central Asia live in these eight affected SBAs, thus the impact of virtual water trade on water scarcity can be considered significant also at regional scale.

Central Asia is generally perceived as a water scarce region, even though its water resources are relatively abundant. My results reinforce the view that the actual problem in the region is not the availability of water resources but its uneven distribution and excessive use. Currently most areas that use their available water resources excessively are also large virtual water exporters. These are also the areas where great majority of the region's population is concentrated, and the pressure on scarce water resources is only expected to grow in the future due to increasing population. Consequently, there is a real need for measures to alleviate water scarcity in Central Asia. Such measures have traditionally included, for example, reducing water use intensity and increasing water use efficiency. In the current globalised world, however, a great deal of water intensive products are not consumed at the place of production but traded elsewhere, thus the wider context of water management cannot be ignored.

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Annex I – Materials used in the analysis

Table A1. Materials used in the analysis, presented in SBA scale.

					Available water	Water consumption (km^3/yr)						Net virtual water
SBA	Basin	Country	Climate zone	Population (10^6)	resources (km^3/yr)	Irrigation	Livestock	Electricity	Manufacturing	Domestic	Total	imports (km^3/yr)
1121	Amu Darya	Afghanistan	Arid	12.532	8.794	7.019	0.030	0.000	0.060	0.133	7.243	0.073
1122	Amu Darya	Afghanistan	Arid	0.034	0.061	0.002	0.000	0.000	0.000	0.000	0.003	0.000
1130	Amu Darya	Afghanistan	Temperate	0.358	0.625	0.165	0.002	0.000	0.000	0.004	0.172	0.003
1140	Amu Darya	Afghanistan	Continental	0.285	1.032	0.021	0.001	0.000	0.000	0.002	0.024	0.000
1520	Helmand	Afghanistan	Arid	7.363	14.000	9.784	0.036	0.001	0.011	0.084	9.916	0.144
2021	Other Basin	Kazakhstan	Arid	0.408	0.792	0.001	0.009	0.005	0.006	0.026	0.048	0.010
2022	Other Basin	Kazakhstan	Arid	0.089	2.675	0.008	0.007	0.005	0.000	0.008	0.028	0.002
2023	Other Basin	Kazakhstan	Arid	0.134	4.052	0.009	0.006	0.000	0.003	0.012	0.029	0.004
2041	Other Basin	Kazakhstan	Continental	0.014	0.362	0.000	0.001	0.000	0.000	0.003	0.004	0.000
2042	Other Basin	Kazakhstan	Continental	0.032	0.336	0.003	0.001	0.000	0.000	0.003	0.008	0.002
2043	Other Basin	Kazakhstan	Continental	0.192	5.612	0.003	0.005	0.001	0.000	0.010	0.019	0.004
2221	Syr Darya	Kazakhstan	Arid	0.000	4.737	0.087	0.001	0.000	0.000	0.001	0.089	-0.001
2222	Syr Darya	Kazakhstan	Arid	0.768	14.532	1.355	0.006	0.000	0.017	0.060	1.439	-0.129
2223	Syr Darya	Kazakhstan	Arid	1.704	9.143	0.666	0.012	0.002	0.020	0.069	0.770	-0.018
2241	Syr Darya	Kazakhstan	Continental	0.208	2.006	0.071	0.005	0.000	0.004	0.017	0.097	0.000
2242	Syr Darya	Kazakhstan	Continental	1.601	3.621	1.427	0.008	0.000	0.033	0.088	1.557	-0.157
2321	Ili	Kazakhstan	Arid	0.673	6.091	0.216	0.007	0.001	0.010	0.032	0.265	-0.002
2322	Ili	Kazakhstan	Arid	0.070	2.688	0.076	0.004	0.001	0.000	0.005	0.085	-0.008
2323	Ili	Kazakhstan	Arid	0.537	0.764	0.287	0.006	0.003	0.011	0.039	0.346	-0.001
2341	Ili	Kazakhstan	Continental	1.411	1.673	0.659	0.008	0.000	0.038	0.094	0.800	-0.029
2342	Ili	Kazakhstan	Continental	0.551	1.183	0.774	0.006	0.000	0.012	0.043	0.834	-0.041
2641	Ob	Kazakhstan	Continental	1.446	11.620	0.062	0.010	0.016	0.030	0.092	0.210	0.012
2642	Ob	Kazakhstan	Continental	1.508	15.961	0.154	0.031	0.002	0.024	0.098	0.309	0.011
2643	Ob	Kazakhstan	Continental	0.950	3.899	0.154	0.012	0.009	0.027	0.070	0.272	-0.009
2644	Ob	Kazakhstan	Continental	1.128	19.382	0.571	0.026	0.038	0.022	0.082	0.739	-0.030
2720	Ural	Kazakhstan	Arid	0.241	2.602	0.164	0.005	0.000	0.000	0.006	0.174	-0.001
2740	Ural	Kazakhstan	Continental	0.903	2.008	0.152	0.007	0.001	0.015	0.049	0.224	-0.006
2820	Volga	Kazakhstan	Arid	0.107	1.238	0.217	0.007	0.004	0.005	0.019	0.252	-0.004
2840	Volga	Kazakhstan	Continental	0.049	1.277	0.027	0.003	0.000	0.000	0.003	0.033	-0.001
3221	Syr Darya	Kyrgyzstan	Arid	1.413	0.580	0.831	0.009	0.016	0.028	0.063	0.948	-0.004
3222	Syr Darya	Kyrgyzstan	Arid	0.276	0.557	0.326	0.005	0.002	0.004	0.010	0.346	-0.004
3223	Syr Darya	Kyrgyzstan	Arid	0.092	0.337	0.077	0.004	0.000	0.000	0.003	0.083	-0.001
3240	Syr Darya	Kyrgyzstan	Continental	1.003	1.398	0.572	0.009	0.000	0.004	0.017	0.602	-0.004
3421	Syr Darya	Kyrgyzstan	Arid	0.116	0.137	0.384	0.001	0.000	0.010	0.024	0.419	-0.010
3422	Syr Darya	Kyrgyzstan	Arid	0.218	0.302	0.286	0.003	0.000	0.000	0.007	0.296	-0.003
3440	Syr Darya	Kyrgyzstan	Continental	2.033	0.383	1.186	0.005	0.003	0.045	0.051	1.290	-0.004
4122	Amu Darya	Tajikistan	Arid	0.114	0.496	0.005	0.002	0.000	0.000	0.002	0.009	-0.001
4130	Amu Darya	Tajikistan	Temperate	3.634	4.254	1.839	0.008	0.014	0.165	0.068	2.093	-0.483
4140	Amu Darya	Tajikistan	Continental	0.696	2.915	0.278	0.008	0.000	0.012	0.018	0.316	-0.028
4220	Syr Darya	Tajikistan	Arid	1.822	0.990	1.738	0.007	0.001	0.117	0.072	1.936	-0.146
5120	Amu Darya	Turkmenistan	Arid	2.176	19.978	4.165	0.011	0.000	0.080	0.125	4.380	-0.664
5921	Caspian Sea	Turkmenistan	Arid	0.094	0.412	0.001	0.001	0.001	0.004	0.007	0.013	0.002
5922	Caspian Sea	Turkmenistan	Arid	2.260	7.685	4.266	0.018	0.016	0.030	0.060	4.390	-1.125
6120	Amudarya	Uzbekistan	Arid	11.447	27.169	9.235	0.058	0.006	0.038	0.374	9.711	-3.886
6221	Syr Darya	Uzbekistan	Arid	0.035	0.119	0.016	0.003	0.000	0.000	0.002	0.022	-0.005
6222	Syr Darya	Uzbekistan	Arid	6.970	1.279	3.298	0.019	0.005	0.065	0.239	3.626	-0.594
6240	Syr Darya	Uzbekistan	Continental	5.688	1.565	3.344	0.024	0.004	0.069	0.218	3.659	-0.812
Total				**75.381**	**213.321**	**55.983**	**0.456**	**0.156**	**1.021**	**2.510**	**60.127**	**-7.944**

Annex II – Crop and livestock commodities

Table A2. Crop and livestock commodities and their extraction rates.

Crop class	HS code	Commodity (crops)	Extraction rate
Wheat	1001	Wheat	1
	1191	Wheat flour	0.79
	110311	Bulgur	0.95
	110321	Pellets of wheat	0.95
	110811	Wheat starch	0.672
	1109	Wheat gluten	0.119
Maize	1005	Maize	1
	071040	Sweet corn, frozen	0.35
	110423	Worked maize	0.45
	110220	Maize flour	0.82
	110313	Groats and meal of maize	0.82
	110812	Maize starch	0.615
	151521	Maize oil, curde	0.027
	151529	Maize oil, other than crude	0.027
Rice	1006	Rice (paddy, brown, milled, broken)	0.78
	110230	Rice flour	0.637
	110314	Groats and meal of rice	0.637
Barley	1003	Barley	1
	110411	Rolled or flaked grains of barley	0.72
	110421	Worked barley	0.396
Rye	1002	Rye	1
	110210	Rye flour	0.8
Millet	110820	Millet	1
Sorghum	1007	Grain sorghum	1
Soybeans	1201	Soybeans	1
	1507	Soybean oil	0.18
	120810	Soya bean flour or meal	0.85
Sunflower	1206	Sunflower seed	1
	151211	Sunflower oil, crude	0.41
	151219	Sunflower oil, other than crude	0.41
Potatoes	0701	Potatoes	1
	1105	Flour, meal and flakes of potatoes	0.2
	071010	Potatoes, frozen	0.5
	110813	Potato starch	0.19
Cassava	071410	Cassava, dried	0.35
	110814	Cassava starch	0.25
Sugar cane	121292	Sugar cane	1
	170111	Cane sugar	0.11
Sugar beets	121291	Sugar beet	1
	170112	Beet sugar	0.14
Oil palm	120710	Palm fruit	1
	1511	Palm oil	0.19
Rapeseed	1205	Rape seeds	1
	1514	Rapeseed oil	0.38
Groundnuts	1202	Ground nuts (in shell or shelled)	0.85
	1508	Ground nut oil	0.301
Pulses	0708	Leguminous vegetables, fresh	1
	0713	Leguminous vegetables, dried	1
	071021	Peas, frozen	1
	071022	Beans, frozen	1
	071029	Other legumes, frozen	1
	110610	Flour or meal of dried legumes	0.72
Citrus	0805	Citrus fruits	1
Dates	080410	Dates	1
Grapes	0806	Grapes, fresh or dried	0.625
Cotton	120720	Cotton seeds	0.63
	151221	Cotton seed oil, crude	0.101
	151229	Cotton seed oil, other than crude	0.101
	5201	Cotton, not carded or combed	0.35
	5203	Cotton, carded or combed	0.333
	5204	Cotton sewing thread	0.333
	5205	Cotton yarn, > 85% cotton	0.333
	5206	Cotton yarn, < 85% cotton	0.665
	5207	Cotton yarn, retail packed	0.333
	5208	Woven cotton fabrics, > 85% cotton, < 200 g/m2	0.316
	5209	Woven cotton fabrics, > 85% cotton, > 200 g/m2	0.316
	5210	Woven cotton fabrics, < 85% cotton, < 200 g/m2	0.632
	5211	Woven cotton fabrics, < 85% cotton, > 200 g/m2	0.632
	5212	Other woven cotton fabrics	0.316
Cocoa	1801	Cocoa beans	1
Coffee	0901	Coffee	1

Livestock product	HS code	Commodity (livestock)	Extraction rate
Bovine	0201	Meat of bovine animals, fresh or chilled	0.47
	0202	Meat of bovine animals, frozen	0.47
Swine	0203	Meat of swine, fresh, chilled or frozen	0.69
Sheep	0204	Meat of sheep, fresh, chilled or frozen	0.5
Fowls	020711	Fowls, not cut, fresh or chilled	0.78
	020712	Fowls, not cut, frozen	0.78
	020713	Cuts and offal of fowls, fresh	0.78
	020714	Cuts and offal of fowls, frozen	0.78
Raw milk	0401	Milk and cream	0.9
	0403	Buttermilk, cream, yogurt etc.	0.8
	0406	Cheese and curd	0.15

Annex III – Virtual water trade: Uzbek cotton

Virtual water content of seed cotton (m^3/kg harvested) was calculated for each SBA based on annual production of cotton (kg/yr) and crop specific consumptive blue water use (m^3/yr), as presented in Table A3.

Table A3. Virtual water content of cotton calculated for Uzbek SBAs.

SBA	Production (kg/yr)	Blue water consumption (m^3/yr)	Virtual water content (m^3/kg)
6120	1,989,800,000	7,117,160,000	3.577
6221	3,111,350	10,403,400	3.344
6222	797,525,000	1,277,120,000	1.601
6240	696,499,000	1,555,810,000	2.234
Uzbekistan total	**3,486,935,350**	**9,960,493,400**	

Exports and imports (kg) of 14 cotton products were converted to equivalent amount of the primary product, i.e. seed cotton, according to specific extraction rates (amount of processed product obtained from processing the primary product) (see Table A4). Because seed cotton produces both cotton seed and cotton lint the conversion to primary product was done separately for cotton seed products and cotton lint products. Only the product group that resulted in larger amount of the primary product (marked with green in Table A4) was taken into account to avoid double counting of the amount of primary product needed to produce the processed products.

Table A4. Exports and imports of cotton commodities converted to equivalent amount of seed cotton. The converted exports and imports are marked with green. Marked with yellow are the trade flows of fabrics, for which an additional process water requirement was estimated.

	HS code	Commodity	Extraction rate	Exports (kg)	Imports (kg)	Exports, converted to primary product (kg)	Imports, converted to primary product (kg)
Obtained from cotton seed	120720	Cotton seeds	0.63	600	20,235	952	32,119
	151221	Cotton seed oil, crude	0.101	236,337	10,960	2,344,617	108,730
	151229	Cotton seed oil, other than crude	0.101	943,425	85,445	9,359,375	847,672
		Total (primary product needed)				**11,704,944**	**988,522**
Obtained from cotton lint	5201	Cotton, not carded or combed	0.35	635,819,188	68,031	1,816,626,252	194,373
	5203	Cotton, carded or combed	0.333	370,039	2,236	1,112,900	6,724
	5204	Cotton sewing thread	0.333	164,917	9,739	495,992	29,291
	5205	Cotton yarn, > 85% cotton	0.333	45,970,828	18,187	138,258,129	54,698
	5206	Cotton yarn, < 85% cotton	0.665	214,997	6,310	323,304	9,489
	5207	Cotton yarn, retail packed	0.333	93,057	4,455	279,871	13,397
	5208	Woven cotton fabrics, > 85% cotton, < 200 g/m2	0.316	10,412,849	895,049	32,965,095	2,833,553
	5209	Woven cotton fabrics, > 85% cotton, > 200 g/m2	0.316	2,883,049	220,092	9,127,184	696,771
	5210	Woven cotton fabrics, < 85% cotton, < 200 g/m2	0.632	3,482	8,926	5,512	14,130
	5211	Woven cotton fabrics, < 85% cotton, > 200 g/m2	0.632	15,394	28,300	24,367	44,796
	5212	Other woven cotton fabrics	0.316	9,648	62,010	30,543	196,311
		Total (primary product needed)				**1,999,249,149**	**4,093,532**
		Fabrics total		**13,324,422**	**1,214,377**		

The converted national exports were divided between SBAs in proportion to the production of cotton and national imports in proportion to the total population of SBAs (Table A5).

Table A5. The converted exports and imports of cotton divided between SBAs.

SBA	Production (kg/yr)	Production (% of country total)	Population	Population (% of country total)	Exports, converted to primary product (kg)	Imports, converted to primary product (kg)	Net imports, converted to primary product (kg)
6120	1989800000	57.1%	11,447,000	47.4%	1,140,860,256	1,941,109	-1,138,919,148
6221	3111350	0.1%	35,000	0.1%	1,783,906	5,876	-1,778,030
6222	797525000	22.9%	6,970,000	28.9%	457,264,336	1,182,041	-456,082,295
6240	696499000	20.0%	5,688,000	23.6%	399,340,651	964,507	-398,376,144
Uzbekistan total	**3486935350**	**100.0%**	**24,139,000**	**100.0%**	**1,999,249,149**	**4,093,532**	**-1,995,155,617**

The processing of cotton fabrics requires a considerable amount of water for bleaching, dying, printing and finishing. Thus, a process water requirement of 0.36 m^3/kg of fabric was assumed, based on the estimations by Chapagain et al. (2006b). The exports and imports of fabrics (marked with yellow in Table A4) were divided between SBAs separately (Table A6) so that the process water requirement could be added in the virtual water flows of each SBA.

Table A6. Exports and imports of cotton fabrics divided between SBAs.

SBA	Production (kg/yr)	Production (% of country total)	Population	Population (% of country total)	Fabric exports (kg)	Fabric imports (kg)	Net imports of fabric (kg)
6120	1989800000	57.1%	11,447,000	47.4%	7,603,506	575,844	-7,027,662
6221	3111350	0.1%	35,000	0.1%	11,889	1,743	-10,146
6222	797525000	22.9%	6,970,000	28.9%	3,047,536	350,661	-2,696,874
6240	696499000	20.0%	5,688,000	23.6%	2,661,491	286,128	-2,375,363
Uzbekistan total	**3486935350**	**100.0%**	**24,139,000**	**100.0%**	**13,324,422**	**1,214,377**	**-12,110,045**

In the final step of virtual water trade calculations the trade flows of each SBA were multiplied with the virtual water content of cotton unique to that particular SBA (Table A7). The process water requirement of fabrics was also added to the virtual water flow of each SBA (Table A7).

Table A7. Net virtual water imports of each SBA calculated based on SBA specific virtual water content of cotton, trade flows converted to seed cotton and process water requirement of fabrics.

SBA	Virtual water content (m^3/kg)	Net imports, converted to primary product (kg)	Net imports of fabric (kg)	Net virtual water imports (m^3)
6120	3.577	-1,138,919,148	-7,027,662	-4,076,240,784
6221	3.344	-1,778,030	-10,146	-5,948,839
6222	1.601	-456,082,295	-2,696,874	-731,320,169
6240	2.234	-398,376,144	-2,375,363	-890,730,908
Uzbekistan total		**-1,995,155,617**	**-12,110,045**	**-5,704,240,701**

Processing water: 0.36 m^3/kg fabric

Annex IV – Results in SBA scale

Table A8. Population under different water scarcity categories, presented in SBA scale. Note: categories that do not appear in the table equal to 0.

				Baseline scenario									Scenario without virtual water							
							Population under water scarcity (x10^6)									Population under water scarcity (x10^6)				
SBA	Basin	Country	Climate zone	WSI (%)	WCI (m^3/c/yr)	Population not under water scarcity (x10^6)	Moderate water stress (MWS)	High water stress (HWS)	MWS + moderate water shortage	HWS + moderate water shortage	Severe water scarcity	Total under water scarcity	WSI (%)	WCI (m^3/c/yr)	Population not under water scarcity (x10^6)	Moderate water stress (MWS)	High water stress (HWS)	HWS + moderate water shortage	Severe water scarcity	Total under water scarcity
1121	Amu Darya	Afghanistan	Arid	83	702	-	-	-	-	-	12.532	12.532	82	708	-	-	-	-	12.532	12.532
1122	Amu Darya	Afghanistan	Arid	5	1,801	0.034	-	-	-	-	-	-	4	1,805	0.034	-	-	-	-	-
1130	Amu Darya	Afghanistan	Temperate	28	1,746	-	0.358	-	-	-	-	0.358	27	1,754	-	0.358	-	-	-	0.358
1140	Amu Darya	Afghanistan	Continental	2	3,620	0.285	-	-	-	-	-	-	2	3,621	0.285	-	-	-	-	-
1520	Helmand	Afghanistan	Arid	72	1,901	-	-	7.363	-	-	-	7.363	71	1,921	-	-	7.363	-	-	7.363
2021	Other basin	Kazakhstan	Arid	7	1,943	0.408	-	-	-	-	-	-	6	1,967	0.408	-	-	-	-	-
2022	Other basin	Kazakhstan	Arid	1	30,070	0.089	-	-	-	-	-	-	1	30,098	0.089	-	-	-	-	-
2023	Other basin	Kazakhstan	Arid	1	30,335	0.134	-	-	-	-	-	-	1	30,365	0.134	-	-	-	-	-
2041	Other basin	Kazakhstan	Continental	1	25,489	0.014	-	-	-	-	-	-	1	25,508	0.014	-	-	-	-	-
2042	Other basin	Kazakhstan	Continental	3	10,529	0.032	-	-	-	-	-	-	2	10,583	0.032	-	-	-	-	-
2043	Other basin	Kazakhstan	Continental	0	29,155	0.192	-	-	-	-	-	-	0	29,176	0.192	-	-	-	-	-
2221	Syr Darya	Kazakhstan	Arid	2	13,534,942	0.000	-	-	-	-	-	-	2	13,532,921	0.000	-	-	-	-	-
2222	Syr Darya	Kazakhstan	Arid	9	18,931	0.768	-	-	-	-	-	-	10	18,763	0.768	-	-	-	-	-
2223	Syr Darya	Kazakhstan	Arid	8	5,366	1.704	-	-	-	-	-	-	8	5,356	1.704	-	-	-	-	-
2241	Syr Darya	Kazakhstan	Continental	5	9,666	0.208	-	-	-	-	-	-	5	9,665	0.208	-	-	-	-	-
2242	Syr Darya	Kazakhstan	Continental	39	2,262	-	1.601	-	-	-	-	1.601	43	2,164	-	-	1.601	-	-	1.601
2321	Ili	Kazakhstan	Arid	4	9,054	0.673	-	-	-	-	-	-	4	9,051	0.673	-	-	-	-	-
2322	Ili	Kazakhstan	Arid	3	38,154	0.070	-	-	-	-	-	-	3	38,044	0.070	-	-	-	-	-
2323	Ili	Kazakhstan	Arid	45	1,424	-	-	-	-	0.537	-	0.537	45	1,422	-	-	-	0.537	-	0.537
2341	Ili	Kazakhstan	Continental	46	1,186	-	-	-	-	1.411	-	1.411	48	1,165	-	-	-	1.411	-	1.411
2342	Ili	Kazakhstan	Continental	67	2,147	-	-	0.551	-	-	-	0.551	71	2,072	-	-	0.551	-	-	0.551
2641	Ob	Kazakhstan	Continental	2	8,033	1.446	-	-	-	-	-	-	2	8,042	1.446	-	-	-	-	-
2642	Ob	Kazakhstan	Continental	2	10,587	1.508	-	-	-	-	-	-	2	10,594	1.508	-	-	-	-	-
2643	Ob	Kazakhstan	Continental	7	4,106	0.950	-	-	-	-	-	-	7	4,096	0.950	-	-	-	-	-
2644	Ob	Kazakhstan	Continental	4	17,178	1.128	-	-	-	-	-	-	4	17,152	1.128	-	-	-	-	-
2720	Ural	Kazakhstan	Arid	7	10,816	0.241	-	-	-	-	-	-	7	10,812	0.241	-	-	-	-	-
2740	Ural	Kazakhstan	Continental	11	2,223	0.903	-	-	-	-	-	-	11	2,216	0.903	-	-	-	-	-
2820	Volga	Kazakhstan	Arid	20	11,588	-	0.107	-	-	-	-	0.107	20	11,551	-	0.107	-	-	-	0.107
2840	Volga	Kazakhstan	Continental	2	26,067	0.049	-	-	-	-	-	-	3	26,045	0.049	-	-	-	-	-
3221	Syr Darya	Kyrgyzstan	Arid	163	410	-	-	-	-	-	1.413	1.413	164	408	-	-	-	-	1.413	1.413
3222	Syr Darya	Kyrgyzstan	Arid	62	2,018	-	-	0.276	-	-	-	0.276	62	2,005	-	-	0.276	-	-	0.276
3223	Syr Darya	Kyrgyzstan	Arid	25	3,662	-	0.092	-	-	-	-	0.092	25	3,655	-	0.092	-	-	-	0.092
3240	Syr Darya	Kyrgyzstan	Continental	43	1,394	-	-	-	-	1.003	-	1.003	43	1,390	-	-	-	1.003	-	1.003
3421	Syr Darya	Kyrgyzstan	Arid	298	1,184	-	-	-	-	0.116	-	0.116	306	1,096	-	-	-	0.116	-	0.116
3422	Syr Darya	Kyrgyzstan	Arid	97	1,387	-	-	-	-	0.218	-	0.218	98	1,371	-	-	-	0.218	-	0.218
3440	Syr Darya	Kyrgyzstan	Continental	335	189	-	-	-	-	-	2.033	2.033	336	187	-	-	-	-	2.033	2.033
4122	Amu Darya	Tajikistan	Arid	2	4,328	0.114	-	-	-	-	-	-	2	4,324	0.114	-	-	-	-	-
4130	Amu Darya	Tajikistan	Temperate	38	1,171	-	-	-	3.634	-	-	3.634	49	1,038	-	-	-	3.634	-	3.634
4140	Amu Darya	Tajikistan	Continental	10	4,189	0.696	-	-	-	-	-	-	11	4,148	0.696	-	-	-	-	-
4220	Syr Darya	Tajikistan	Arid	181	543	-	-	-	-	-	1.822	1.822	195	463	-	-	-	-	1.822	1.822
5120	Amu Darya	Turkmenistan	Arid	19	9,179	2.176	-	-	-	-	-	-	22	8,874	-	2.176	-	-	-	2.176
5921	Caspian Sea	Turkmenistan	Arid	4	4,370	0.094	-	-	-	-	-	-	3	4,390	0.094	-	-	-	-	-
5922	Caspian Sea	Turkmenistan	Arid	42	3,401	-	-	2.260	-	-	-	2.260	57	2,903	-	-	2.260	-	-	2.260
6120	Amu Darya	Uzbekistan	Arid	21	2,374	-	11.447	-	-	-	-	11.447	36	2,034	-	11.447	-	-	-	11.447
6221	Syr Darya	Uzbekistan	Arid	14	3,448	0.035	-	-	-	-	-	-	18	3,303	0.035	-	-	-	-	-
6222	Syr Darya	Uzbekistan	Arid	237	183	-	-	-	-	-	6.970	6.970	284	98	-	-	-	-	6.970	6.970
6240	Syr Darya	Uzbekistan	Continental	182	275	-	-	-	-	-	5.688	5.688	234	132	-	-	-	-	5.688	5.688
Total						**13.950**	**13.604**	**10.450**	**3.634**	**3.285**	**30.457**	**61.430**			**11.774**	**14.180**	**12.051**	**6.919**	**30.457**	**63.607**