Bachelor thesis

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Criticality of blue virtual water imports of agricultural products for cities.

Analysis for Berlin and Amman from 1998-2002

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Abstract

One major global challenge today is achieving food security for the growing world population, whereas on the other side ecosystem functions have to be secured. Many economies are water-scarce and therefore do not have resources to produce sufficient products to cover own national demands. To remedy these deficits the regions are dependent on virtual water trade based on the import of products from other parts of the world.

The thesis calculated blue virtual water flows for the cities Berlin and Amman at a high spatial resolution of 5arcmin. It presents source regions of 19 crops on subnational level. Furthermore, criticality maps have been created which combine water imports with a criticality based on environmental flow requirement transgressions.

Many differences have been found regarding blue virtual water imports of the cities whereas Amman's imports are 4.78 times higher than Berlin's. While Berlin imports most of its water from the Mediterranean region, the USA and Germany Amman's imports focus on the MENA region including Jordan and the USA. Furthermore, Amman imports more blue water from critical areas (41.44%) than Berlin (29.04%).

However, for a further analysis regarding the share of different cities on environmental flow transgressions in sourcing regions more detailed data and also green virtual water flows would be necessary.

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List of abbreviations

AF	annual flow
EF	environmental flow
EFR	environmental flow requirements
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GCWM	Global Crop Water Model
JRV	Jordan Rift Valley
LPJmL	Lund-Potsdam-Jena managed Land
MAF	mean annual flow
MENA	Middle East an North Africa
MMF	mean monthly flow
UNHCR	United Nations High Commissioner for Refugees
VMF	Variable Monthly Flow

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1 Introduction

With an estimated world population of 8.9 billion in 2050 and changing diets, there will be an increasing demand for food which presents a challenging task for the agricultural sector (United Nations Report, 2004).

Agricultural practices require large amounts of green and blue water, especially as humans already have a major impact, transforming natural vegetation to cropland regarding water extraction for crop production (Siebert and Döll, 2010). The overexploitation of freshwater sources is a great problem in many regions of the world and agriculture is the largest factor accounting for 70% of global freshwater withdrawals (Campbell *et al.*, 2017).

Rising food demands can be met today only due to a globalized trade market. Many countries do not have sufficient water resources to meet the food demands of their own inhabitants. To compensate domestic deficits, economies have to import commodities and as a consequence the water used during the production process from other regions. This water is called *virtual water* and dates back to the work of Tony Allan in the early 1990s. Some estimations quantify the global volume of virtual water related to international trade at 1625 km^3 yr^{-1} for the period 1997-2001 (Chapagain and Hoekstra, 2004). 61% of these flows are related to crops and crop products while the remaining percentages subdivide into 17% livestock products and 22% industrial products.

Net import regions of virtual water are East Asia, Central America, North and West Africa and the Middle East (Yang *et al.*, 2006). The concept shows that access to water resources is not limited by watersheds anymore (Siebert and Döll, 2010) and water scarce nations benefit from the possible saving of water through import of water intensive products. Chapagain *et al.* (2006) calculated that the actual value of saving global water resources for the time period of 1997 – 2001 was 352 Gm^3yr^{-1}. This illustrates that virtual water could be a solution for the increasing water scarcity in some regions, but it might also lead to a shift of production and associated pressure on scarce water resources in the areas facing these problems.

There are various previous studies on virtual water flows for different sectors, most of them focus on international trade of countries (Hoekstra and Hung, 2002; Chapagain, Hoekstra and Savenije, 2006; Yang *et al.*, 2006). Studies which determine virtual water trade on a subnational level are scarcer. However, high resolution data is inevitable, as countries contain many different and diverse regions with strongly varying water availabilities.

In this thesis, the Global Crop Water Model (GCWM) with a 5arcmin spatial resolution and input data from 1998 to 2002 was used. 19 major crop groups were included which covered 71% of the global harvested cropland during that time period (Hoff *et al.*, 2014). The model calculates specific crop water uses and crop yields in rainfed and irrigated agriculture and can simulate flows of commodities and their green and blue virtual water content. This study focuses on the blue virtual water trade only.

A first approach of analysing water footprints of cities with the GCWM was already made by Hoff *et al.* in 2014. They assumed that the urbanization processes, the rapid economic development and also the changing lifestyles in cities are major drivers for water and resource demands which are growing faster than the national average and focused therefore on the analysis of city footprints. This bachelor thesis will also focus on cities, more precisely on Berlin (Germany) and Amman (Jordan).

The aim of this analysis is to identify how much blue virtual water the cities imported in total during the time period 1998 – 2002, from which source regions these imports came from, hence how much water the cities imported from critical regions. This criticality analysis is based on the concept of environmental flow requirements (EFRs), which are defined by the flow regime required in a river to achieve desired ecological objectives (Acreman and Dunbar, 2004). Required data was taken from a study of Jägermeyr *et al.* (2017) where EFR deficits have been calculated for the simulation period 1980-2009. For this thesis, the transgressions of the EFRs have been calculated as long-term averages per month.

This study first presents a general view on the study area and the concepts of virtual water and environmental flow requirements. Afterwards, the data and methods which have been used are further explained. The thesis focuses later on the results and the analyzation of the criticality maps which have been created from blue virtual water imports and EFR transgression data. Finally, the study closes with the discussion.

The main focus of the discussion part is on the interpretation of the results regarding imports and source regions of both cities. Also, the criticality maps will be analysed, and limitations and uncertainties of the models and the data presented.

2 Study area

This thesis focuses exemplary on the cities Berlin and Amman which are hot spots regarding population density, food demand and changing lifestyles. Berlin presents import patterns of a developed, water-abundant economy, conversely Amman of a developing and water-scarce one. To understand virtual water imports of the cities basic knowledge about agriculture, trade patterns and virtual water flows within the countries is important and will be shortly raised in this chapter. The focus in on Berlin, because data already existed. Amman was chosen freely as a capital of a water-scare country.

2.1 Berlin and Germany in general

Germany is characterized by a temperate and marine climate. Even though 3/5 of the rainwater evaporates, water availability totals 188 km^3 and makes Germany a water-abundant country (BMU, 2014). Agriculture is an important sector using approximately 17 million ha which presents more than half of the total area of Germany. Important federal states regarding agricultural production are as for instance Mecklenburg-Western Pomerania, Brandenburg, Bavaria and Lower Saxony.

Being part of the European Union (EU) Germany benefits from the European single market which guarantees the free movement of goods, capital, services and labor in the EU. The single market connects the EU member states: Germany sends 75% of all its exports to the EU whereas 67% of all its imports come from countries within the EU (BMEL, 2018).

Germany is a key importer of water through traded agricultural products, on the other side countries in the East and South of the EU are specialized in water-intensive agricultural production and are therefore key exporters of water (Serrano *et al.*, 2016). Countries in the Mediterranean area (France, Greece, Italy, Portugal and Spain) have a specific high share on blue water resources as the majority of irrigated areas in the EU are concentrated in this region. According to Wriedt *et al.* (2008) the above listed countries account for 75% of the area equipped for irrigation in the EU. Global agricultural imports of Germany amount to 35 million tons of products and hence, more than 65 $km^3 yr^{-1}$ of water (BMU, 2014). Regarding blue water, Germany is the largest importer in the EU. Furthermore, Germany is also a large exporter of agricultural products. The agricultural sector generates ¼ of its sales revenue from exports (BMU, 2014).

Berlin is located in the Northeast of Germany. With its steadily increasing population which amounted to approximately 3.5 million during the analyzed time period from 1998 – 2002 the capital is a net importer of crops and crop-related water in Germany.

2.2 Amman and Jordan in general

Jordan is an arid and semiarid country with an annually average precipitation of 8.2 km^3 of which 80% are lost to evaporation (Abu-Sharar, Al-Karablieh and Haddadin, 2012). The country can be divided in very diverse climates: the desert climate called Badia, the Mediterranean climate in the Highland regions and the semi-tropical climate in the Jordan Rift Valley (JRV). Thanks to this diversity the production of off-season fruits and vegetables is possible. Agriculture is an important sector in Jordan as it employs 3.8% of the country's labor force (World Bank, 2008).

In the JRV mostly banana and citrus orchards are planted (Abu-Sharar, Al-Karablieh and Haddadin, 2012). These products are very water intensive therefore high amounts of irrigation are needed. However, irrigation efficiency in Jordan and the Middle Eastern and North African (MENA) region in general is very poor. Also water conservation practices are very unsatisfying due to the occurrence of technical issues, e.g. uneven pressures in pipe distribution networks, low water quotas or poorly designed on-farm micro-irrigation equipment (Abu-Sharar, Al-Karablieh and Haddadin, 2012).

Farming in the Highland and Badia is also dealing with serious water problems. Many farms depend on the extraction of water from unlicensed wells whereas in general the groundwater aquifers are over-pumped (Abu-Sharar and Battikhi, 2002). These aquifers are very valuable, hence the practice of over-pumping is dangerous for their sustainability (El-Naqa and Al-Shayeb, 2009).

Jordan's food security heavily depends on imports. Abu-Sharar *et al.* (2012) calculated that the virtual water embedded in cereal imports alone would have exceeded the total blue water resources of Jordan by 3.7 times in 2006. Furthermore, the current potential of cultivated land which totals 400.000 ha would not have been sufficient to cultivate the amount of crops which would have needed an area about 876.414 ha.

Jordan is not involved in a complex single market like the EU. Trade relations in the MENA region are dominated by bi-lateral contracts, but until now no market exists that involves all MENA countries.

Jordan's capital Amman is located in the central North of the country. It is the important center of communication, commerce, banking and industry of Jordan. During the analyzed period the city hosted 1.9 million people. Taking a brief view on the present situation, the actual population size of Amman with 2.4 million citizens (Makhamreha and Almanasyeha, 2011) reveals that the city population is increasing very fast. Jordan always received and still receives migrants as the country hosted several refugee waves and displaced persons due to conflicts in the Middle East, all along Palestinians who have been expelled from their home land through occupation and the ensuing wars in 1948 and 1967. Nowadays the country inhabits 740.160 refugees, whereas the main part comes from Syria. About 81.1% of them are living in urban areas, the majority in the capital (UNHCR, 2018).

3 Basic concepts

3.1 Virtual water

The term virtual water was introduced by Tony Allan who defined it as the water needed to produce (agricultural) commodities (Allan, 2003). Hoekstra and Chapagain (2008) drew attention to the fact that water needed to produce a good is a hypothetical term and not equivalent to water used to produce this good. Furthermore, they indicated that the term *virtual* refers to the fact that a great amount of the water used in the production process is not included in the final product. The concept virtual water links water, trade and food – as water resources are redistributed on a global level (Antonelli and Tamea, 2015) – and raises awareness to local water shortages. These occur because of an increasing water demand which is driven by four main factors (Antonelli and Tamea, 2015):

1. an increasing population,
2. rising standards of living, industrial activities and energy demands,
3. a dietary shift towards higher calorie intake of (water-intensive) animal-based products
4. and the impact of climate change

3.1.1 History of the term *virtual water*

Before 1993 Tony Allan used the term *embedded water* which did not gain much attention from the water community (Allan, 2003). The idea became better known when Allan started using the term *virtual water* in the second half of the 1990s. However, many economists and engineers still did not accept the concept and the term, because of its unclear and confusing character. During that time period, Allan studied water shortages in the Middle Eastern and North African region and wondered how these countries could deal with the immense water shortage. The water demand in the region began to exceed the supply in the early 1970s and in some countries even in the 1950s (Allan, 1998).

Nowadays the MENA region has the largest water deficit in the world. The availability of freshwater per capita amounted 4000m^3 yr^{-1} in 1950 and decreased to 1100m^3 yr^{-1} in 2007 (The World Bank, 2007). Projections for the years 2040-2050 show that 2/3 of the regions' countries will have less than 200m^3 yr^{-1} per capita (Antonelli and Tamea, 2015). Of all water-scarce MENA countries Jordan, Oman and Tunisia will experience major problems of water supply in the future, but only Jordan approaches a crisis situation (Beaumont, 2002).

Consequently, the MENA countries became main net importers of agricultural products. Despite these water shortages, the region's dependence on resources had been ignored for a long time in the global trading systems and hydro-politics. Allan found that the reason for this ignorance was the stakeholders' awareness of the destabilizing potential of a publicly communicated dependence on water and staple foods coming from outside the own country. He defined virtual water as *economically invisible* and *politically silent* (Allan, 2003). These characteristics offer water policy-makers and managers the opportunity to create a policy discourse where it can be supposed that no national resource or food deficit exists (Allan, 2003). This shows that virtual water is not just about shifting resources in form of products from one country to another, but that the concept is a major political issue. Thus, many studies focused on the importance of (virtual) water as a political instrument of power (Bakker, 2012; Beltrán and Velázquez, 2015; Beltrán and Kallis, 2018). Bakker (2012) stated that commodities (e.g. staple foods) are always connected to power relations and that water transgresses not just geographical but also geopolitical boundaries which, as a result, makes it a political and biopolitical resource.

3.1.2 Advantages and disadvantages

The most important virtue of virtual water is the possibility for water-scarce economies to remedy their deficits by moving water from advantaged regions to disadvantaged ones. This contains a national, but also global potential to save water. Diverse export regions need different amounts of water to produce one product. Table 1 shows the average virtual water content in m^3 per ton for some products in different countries. The production of wheat for example needs 734 m^3 per ton of virtual water in Japan compared to 2421 m^3 per ton in Italy while the world average lies at 1334 m^3 per ton.

Table 1: Average virtual water content (m^3 per ton) of some selected products in different countries

	USA	China	India	Russia	Indonesia	Australia	Brazil	Japan	Mexico	Italy	Netherlands	World average*
Rice (paddy)	1275	1321	2850	2401	2150	1022	3082	1221	2182	1679		2291
Rice (husked)	1656	1716	3702	3118	2793	1327	4003	1586	2834	2180		2975
Rice (broken)	1903	1972	4254	3584	3209	1525	4600	1822	3257	2506		3419
Wheat	849	690	1654	2375		1588	1616	734	1066	2421	619	1334
Maize	489	801	1937	1397	1285	744	1180	1493	1744	530	408	909
Soybeans	1869	2617	4124	3933	2030	2106	1076	2326	3177	1506		1789
Sugar cane	103	117	159		164	141	155	120	171			175
Cotton seed	2535	1419	8264		4453	1887	2777		2127			3644
Cotton lint	5733	3210	18694		10072	4268	6281		4812			8242
Barley	702	848	1966	2359		1425	1373	697	2120	1822	718	1388
Sorghum	782	863	4053	2382		1081	1609		1212	582		2853
Coconuts		749	2255		2071		1590		1954			2545
Millet	2143	1863	3269	2892		1951		3100	4534			4596
Coffee (green)	4864	6290	12180		17665		13972		28119			17373
Coffee (roasted)	5790	7488	14500		21030		16633		33475			20682

Source: Hoekstra and Chapagain, 2006

These differences depend heavily on climate and therefore growth conditions, technology adopted for farming and many other factors influencing water use efficiency (Hoekstra and Chapagain, 2006).

Chapagain *et al.* (2006) studied the global water saving potential through international trade. They analyzed international virtual water flows considering all major crop and livestock products from 1997 – 2001 and showed that if all products would have been produced domestically an amount of 1605 $Gm^3\ yr^{-1}$ would have been needed. With international trade the studied products just needed 1253 $Gm^3\ yr^{-1}$ which implicates that 352 $Gm^3\ yr^{-1}$ could be saved globally. De Fraiture *et al.* (2004) also analyzed international trade especially the impact of international cereal trade on the global water use. Their study also verified that virtual water trade offers the potential to reduce the national and global water use arguing that it needs 500 – 4000 l on the national level to produce 1kg of cereals.

However, De Fraiture *et al.* (2004) furthermore stated that the role of virtual water regarding global water use is solely modest. The potential of international trade seems to be large, but it often occurs for reasons unrelated to water and follows the path of political and economic benefits. Yang *et al.* (2006) confirm that low income countries do not play a great role in global virtual water trade. Reasons for that are the minor ability to exploit own natural resources and to invest in agriculture because of the low income. If a nation does not have many financial capabilities also the choice of purchasing food from the international market contracts especially when the domestic food supply is in shortage (Yang *et al.*, 2006).

Besides the possible potential of saving water, virtual water is as previously mentioned also a political mean, because it is silent and therefore not politically controversial. Furthermore, it is an economical solution: virtual water embedded in a specific commodity produced in a water-rich country can be traded at less than its production cost in a water-deficient one (Chapagain, Hoekstra and Savenije, 2006)

On the other hand, there are drawbacks: economies, as for instance in the MENA region, are strongly dependent on imports from other countries. Furthermore, small economies often do not benefit to a great extent from international trade which mainly occurs between large, water-rich economies (Gerten, 2018). A third negative effect are environmental impacts (Yang *et al.*, 2006). Virtual water flows can cut problems from one country, but often in the same time affect a second one regarding ecological impacts. Finally, virtual water trade can have many social and political impacts on the export regions, especially local communities living there.

3.2 Environmental flow requirements

This thesis will take into account the issue of environmental impacts by having a look at the source regions of virtual water imports. This abstract refers to the concept of environmental flow requirements whose basic idea will be explained here.

Environmental flows (EFs) can be defined as the flow regime which is required in a river to accomplish desired ecological objectives (Acreman and Dunbar, 2004).

According to Smakhtin (2008) environmental flow requirements (EFRs) are effectively a sector or consumer of water, like agriculture, industrial and domestic users. Numbers of AQUASTAT

(FAO, 2010) show that global water withdrawals around the year 2003 summed up to 3856 km^3 whereas 70% of the withdrawals refer to the agricultural, 19% to the industrial and 11% to the domestic sector.

For a long time, ecosystems were regarded as something that can be exploited endlessly without recognizing the importance of maintaining their stability. The Earth Summit in Rio de Janeiro (1992) supported the conservation of ecosystems as a public good, independent of their utility as a resource, implicating that not just mankind, but also other species and the ecosystems themselves should have a right to water (Acreman and Dunbar, 2004). In order to guarantee this right, attention must be paid to the various factors determining the health of a river system (Norris and Thoms, 1999). The Brisbane Declaration (2007) promoted a global action agenda for the urgent need to protect rivers globally, because freshwater ecosystems are a foundation of social, cultural and economic well-being. Thus, EFRs are essential for the health of freshwater ecosystems.

3.2.1 Environmental flow approaches

The first environmental flow approaches focused on minimum flow levels only, because the conventional knowledge was that ecological problems solely occur when this level is transgressed. Nowadays many authors pay attention to all elements of a flow regime, as different elements have different responsibilities (Poff *et al.*, 1997; Knights, 2002; Smakhtin, 2008). Medium levels are important for e.g. fishing migration and cycling of organic matter from river banks. High flows maintain ecosystem productivity and diversity e.g. the transport of fine sediments, wetland flooding and bird breeding. Additionally, low flows provide many ecological benefits as they present recruitment opportunities for some species, are important for algae control and the use of the river by local people e.g. the Ribeirinhos in Brazil. All those components interact in complex ways.

Pastor *et al.* (2014) calculated that more water is needed for EFs during low-flow periods (46–71 % of average low-flows) compared to high-flow periods (17–45 % of average high-flows).

Changes in the flow regime always have an influence on the river system. Therefore, the basic idea is to maintain a natural river system, so the EF is close to the natural variability of the flow regime. The flow variability is responsible for the composition, diversity, productivity and resilience of freshwater-dependent ecosystems (Smakhtin, Revenga and Döll, 2004).

Different methods to estimate EFs exist. They can be divided into local methods which are applied on a river or basis scale and global methods. Local methods consist of four categories: *hydrological*, *hydraulic*, *habitat simulation* and *holistic* methods (Pastor *et al.*, 2014). *Hydrological* methods are based on hydrological data for advising environmental flow scales whereas a fixed proportion of flow represents the EFR intended to preserve (Tharme, 2003). Their advantages are that they are simple and fast and thus frequently used in preliminary assessments. *Hydraulic* methods are often applied at a local scale when river cross-section measurements are available. They are based on changes in hydraulic variables (Tharme, 2003). On the contrary, *habitat simulation* methods take a closer look at ecohydrological relationships. They are based on correlations between hydraulic parameters and certain species (Pastor *et al.*, 2014). Finally, *holistic* methods combine the three mentioned approaches with expert knowledge, therefore assessing the entire ecosystem. Their great advantage is the interdisciplinarity, combining hydrological, geomorphological, biological and sociological methods (Pastor *et al.*, 2014).

EFRs depend on the objective of the environmental water management. Smakhtin *et al.* (2004) distinguish between four statuses (Table 2), starting with the *natural condition* where no modifications occurred. The second status is the *good condition* where ecosystems are slightly or moderately modified. Hereafter, the third status, the *fair condition*, implies a moderate modification and a reduction of sensitive biota in numbers and extent, whereas the last status is represented by the *poor condition*. In this status, ecosystems are already critically modified. As most ecosystem functions and services are lost in this stage, the poor condition should not be considered acceptable from a management perspective.

Table 2: Conservation statuses

Conservation status or management objective	*Ecological description*	*Management perspective*	*Corresponding low-flow characteristic as a measure of LFR*
Natural (unmodified)	Pristine condition or negligible modification of in-stream and riparian habitat	Protected rivers and basins. Reserves and national parks. No water projects (dams, diversions etc.) allowed.	Q50
Good (slightly or moderately modified)	Largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Minor water supply schemes or irrigation development present and / or allowed.	Q75
Fair (moderately or considerably modified)	The dynamics of the biota have been disturbed. Some sensitive species are lost and/or reduced in extent. Alien species may occur.	Multiple disturbances associated with the need for socio-economic development, e.g. dams, diversions and transfers, habitat modification and water quality degradation.	Q90
Poor (critically modified and degraded)	Habitat diversity and availability have declined. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Management intervention is needed to restore flow pattern, river habitats etc. This status is not acceptable from the management perspective.	N/A

Source: Smakhtin, Revenga and Döll, 2004

3.2.2 Linkages between environmental flows and agricultural production

Some sources estimate that the world population in 2050 will amount to 8.9 billion (United Nations Report, 2004). Already nowadays do 2/3 of the global population (4 billion people) live under conditions of severe water scarcity during at least one month of the year (Mekonnen and Hoekstra, 2016). As the population trend is straightened upward, more agricultural production will be necessary to cover the food demand which also increases global irrigation numbers. But rivers and their life-supporting functions have to be saved too. Agriculture and especially crop production consumes the largest amount of water and therefore heavily relies on river systems.

As soon as irrigation is used for agricultural production many losses on the field occur due to evaporation on soil, infiltration, runoff and many other processes. This shows that the water withdrawals are always higher than the actual plant physiological need (Gerten, 2018). Alexandratos *et al.* (2012) studied varying irrigation efficiencies of different regions. They defined irrigation efficiency as the ratio between crop water requirements (which are estimated as the sum of consumptive water use in irrigation, water needed for land preparation and weed control in case of paddy rice) and irrigation water withdrawal. The average efficiency for the world amounts 50% for the years 2005 and 2007 and varies strongly from 25% in areas with high water values to 58% in South Asia. Improving the water use efficiency is a very slow and difficult process which still could increase marginally at the global level and water abundant regions but way more in water scarce areas. The study shows that an increase of 9% in the MENA region would be possible.

Many irrigation withdrawals are responsible for global EFR transgressions. If the EFRs would be considered globally losses in production would occur. Jägermeyr *et al.* (2017) calculated that 41% of the current irrigation water use which in total accounts for 70% of all withdrawals is based on the expense of EFRs.

An approach to link EFRs with the increasing population and agriculture was made by Rockström *et al.* (2009b). They developed and introduced the Planetary Boundaries concept. It presents nine planetary boundaries, inter alia the Freshwater Boundary, defining a safe operating space for humanity. Transgressing these boundaries causes a destabilization of the current state of the planet. Rockström *et al.* (2009b) suggested for the Freshwater Boundary a value of 4000 $m^3\ yr^{-1}$ with a zone of uncertainty of 4000-6000 $m^3\ yr^{-1}$. The control variable used for this calculation was the global consumptive use of blue water. Based on these findings Gerten *et al.* (2013) suggested a bottom-up qualification of local water availabilities based on the EFRs. They drew the boundary at 2800 $m^3\ yr^{-1}$ with an uncertainty zone of 1100 – 4500 $m^3\ yr^{-1}$. Steffen *et al.* (2015) reported a new assessment to complement the boundary with a basin-scale boundary for the maximum rate of blue water withdrawal along rivers, which is also based on the EFRs.

Even though these approaches have been criticized inter alia because of the spatial and temporal variability in freshwater availability, leading to the fact that no ecological thresholds for freshwater use can be considered as strictly global (Nordhaus, Shellenberger and Blomqvist, 2012), they offer a global view on the connectivity of earth systems. Especially, the Freshwater Boundary links major global tasks like water availability, agriculture and population growth.

3.2.3 Global water scarcity and EFR transgressions

Many studies regarding global EFR transgressions and water scarcity exist.

Hoekstra *et al.* (2012b) for instance measured the blue water footprint based on consumptive use of groundwater and surface water flows. They calculated EFRs and water availability per month at high spatial resolution of 5arcmin and determined that agriculture is with 92% the main factor for the global water footprint. During the whole year a large blue water footprint occurs at the Indus and Ganges River Basins because of the high irrigation patterns all year long. Furthermore, Hoekstra *et al.* (2012b) found that 55% of the river basins studied have a blue water footprint which exceeds blue water availability in at least one month of the year. Additionally, they determined rivers which have a large blue water footprint during a part of the year, namely the Murray-Darling River (Australia), the Colorado River (USA and Mexico), the Krishna River (India), the rivers Euphrat and Tigris (Turkey, Syria and Iraq), the Huang He River (China).

Furthermore, Mekonnen *et al.* (2016) studied imbalances of freshwater demand and availability on a monthly basis for the years 1996 - 2005 at a high spatial resolution of 30arcmin. All year low water scarcity occurs in the Amazon Basin, the Congo Basin, in Malaysia and Indonesia and the subarctic parts of the world. Moderate water scarcity especially in the summer-spring period appears in the Western parts of the USA, Southern Europe, Turkey, Central Asia and Northern China. Moderate water scarcity arises more than half of the year in regions like Northern Mexico, Northern Africa, Pakistan and the MENA region. High water scarcity occurs mainly in densely populated areas, regions where much irrigation occurs (High Plains of the USA) or where a high population and much irrigation is present like in India. Of course, those areas with a low natural water availability like the Sahara are disadvantaged in particularly.

The findings of this thesis will be compared to previous global results in the discussion part.

4 Methods and Data

This chapter gives an insight into models and data used for this bachelor thesis. Data has been edited and results have been calculated with the statistical software R. The scripts can be found in the Supplementary Material. Additionally, the results have been visualized with QGIS. Figure 2 to 18 and also Table 4 have been produced independently.

4.1 Global Crop Water Model

The blue virtual water imports of Berlin and Amman as well as the associated source regions were calculated by the Global Crop Water Model (GCWM). This model was already used by Hoff et al. (2014) for defining city footprints, hence this thesis builds on the aforementioned. On this account, raw data for Berlin, based on city assigned grid cells at high spatial resolution of 5arcmin, already existed. Grid cells for Amman were defined and calculated specifically for this thesis (Supplementary Material).

4.1.1 General input data and calculations

The GCWM has been developed to simulate crop water use and crop yields in rainfed and irrigated agriculture. For the calculation of virtual water flows the model combines specific crop water use and production data for 19 crops: wheat, barley, rye, maize, rice, sorghum, millet, pulses, soybeans, groundnuts, sunflower, rapeseed, potatoes, cassava, grapes, citrus, dates, cocoa and coffee. It is important to mention that the water intensive crop cotton is not included in this approach. The 19 crops covered 71% of the global harvested cropland during the analysed time period 1998 – 2002 (Hoff *et al.*, 2014).

The GCWM is based on the global land use data set MIRCA2000 which simulates cropping patterns and cropping seasons of each crop. Furthermore, daily soil water balances are determined to calculate evapotranspiration of every single crop per grid cell. For irrigated crops fractions of blue and green crop water use were computed (Siebert and Döll, 2008).

The virtual water content of a crop is specified as the amount of water which is needed to produce a unit of harvested crop (VWC_T). Siebert and Döll (2010) computed the content in $m^3\ Mg^{-1}$ as:

$$VWC\_T = \frac{CWU\_T}{PT}$$

where CWU_T is the total consumptive water use of a crop ($m^3\ Mg^{-1}$) and PT is the total crop production ($Mg\ yr^{-1}$). In this thesis just blue virtual water and therefore the consumptive blue crop water use is taken into consideration which is defined as the amount of evapotranspiration on cropland arising from irrigation (Siebert and Döll, 2010).

4.1.2 Virtual water flows of cities

To calculate flows of products and water contents a specific grid cell-based algorithm has been applied (Figure 1), assuming that the per capita consumption of commodities in a country ($CONSD\_CAP_{crop,\ country,\ year}$) is the same for all inhabitants (Hoff *et al.*, 2014):

$$\mathrm{CONSD\_CAP}_{\mathrm{crop,country,year}} = \frac{(PROD_{crop,country,year} - EXPORT_{crop,country,year})}{POP_{country}}$$

where $PROD_{crop,country,year}$ is the production and $EXPORT_{crop,country,year}$ the export of the commodity in the specific country and year in $kg\ yr^{-1}$. $POP_{country}$ refers to the population in the country in the year 2000 based on the HYDE-database.

Crop production data calculated by the GCWM is harmonized to FAO statistics at country level around the year 2000.

The crop consumption in a country, e.g. consumption of barley in Germany, was calculated as the sum of the barley imports of Germany with the barley production in Germany subtracted by the barley export of the country. Different diets and calorie compositions in specific countries are not explicitly distinguished.

In the consumption of food crops their use as livestock feed and their use for producing bioenergy are already included. The analysis does not account for livestock feed other than food crops and imports of livestock products (Hoff *et al.*, 2014).

If one grid cell produces a higher crop amount than the amount consumed by this grid cell it is defined as a surplus area and therefore export cell. This creates imbalances in a country where agricultural regions are main exporters of crops (surplus regions) and cities are main importers (deficit regions). To level out these imbalances the surpluses are distributed iteratively: first to the nearest deficit location and then to larger distances within the country. Outside the country borders the algorithm is fed with UN Comtrade data which defines bi-national trade flows (exports and imports of each country) as well as the country's trade partners. This data was cleared from re-exports before which means that a country can only export what it produces within the own country borders (e.g. Germany cannot export coffee, because it is just importing the product, but not producing it on its own). Imports from other countries are distributed to cells with higher population numbers first.

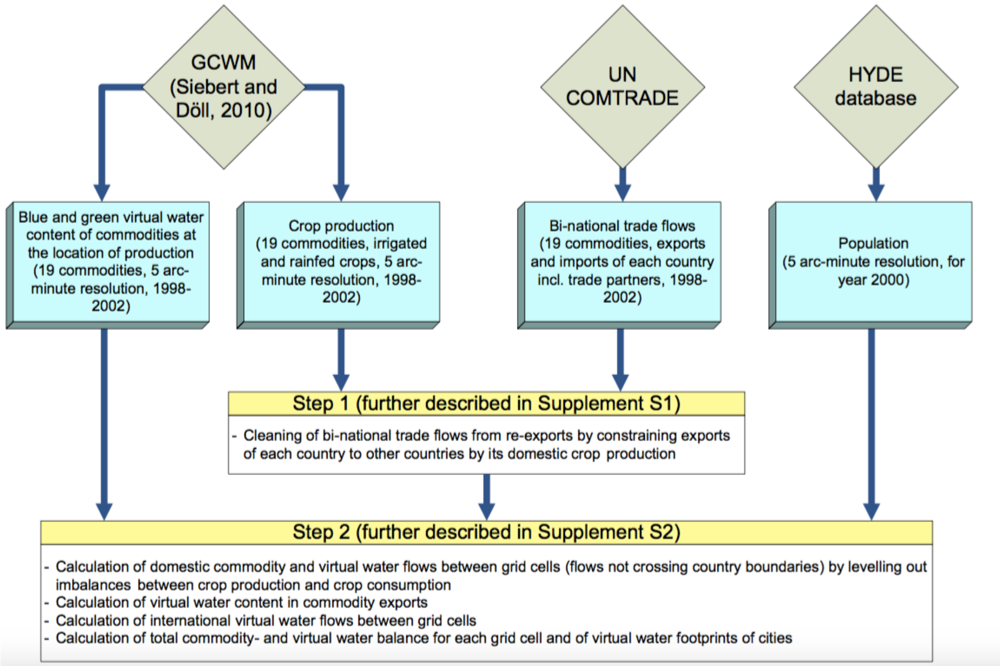


Figure 1: GCWM flowchart (Hoff et al., 2014)

This new approach defines the work from earlier studies as it is now possible to say that a specific grid cell or an accumulation of grid cells, e.g. Berlin imports a specific amount of crops and therefore virtual water not just from a country, but from specific surplus cells in a country. It is still not possible to tell which exact grid cell e.g. in Brazil exports coffee to Berlin, but the model defines a set of coffee export grid cells in Brazil and decides arbitrarily which one exports to Berlin. This grid cell-based analysis is important if ecological or social conditions in the source regions are also taken into consideration.

Applying the algorithm, the model simulates flows of commodities and also blue virtual water on international level, but also commodity and blue virtual water balances for each grid cell and therefore for Berlin and Amman.

4.2 Environmental flow requirements

The blue virtual water imports and their source regions have been calculated with the approach described above. This thesis also aims to combine these results with a specific criticality which is based on the in chapter 3 introduced concept of environmental flow requirements. Therefore, data from Jägermeyr *et al.* (2017) was taken.

4.2.1 Methods

Table 3: EFR methods

EFR method	**Flow regime classification**		**Environmental flow requirements**		
	low-flow	high-flow	low-flow	intermediate-flow	high-flow
$\text{Tessmann}_{\text{adapted}}$	$MF \leq 40\%\ AF$	$MF > AF$	$80\%\ MF$	$40\%\ AF$	$40\%\ MF$
VMF	$MF \leq 40\%\ AF$	$MF > 80\%\ AF$	$60\%\ MF$	$45\%\ MF$	$30\%\ MF$
$\text{Smakhtin}_{\text{adapted}}$	$MF \leq 80\%\ AF$	$MF > 80\%\ AF$	$Q_{90} + h$	–	$Q_{50} + h$
			$h = \begin{cases} 0, & \text{if } Q_{90} > 30\%\ AF \\ 7\%\ AF, & \text{if } Q_{90} \leq 30\%\ AF \\ 15\%\ AF, & \text{if } Q_{90} \leq 20\%\ AF \\ 20\%\ AF, & \text{if } Q_{90} \leq 10\%\ AF \end{cases}$		
			$EFR = min(EFR, 80\%\ MF)$		

Source: Jägermeyr *et al.*, 2017

The authors used three hydrological EFR estimation methods (Table 3) to reflect methodological uncertainties and various policies concerning the fraction of the river flow which should remain untouched. These three methods are the Variable Monthly Flow method, an adaptation of the Tessmann method and an adaptation of the Smakhtin method.

The Variable Monthly Flow method (VMF) was developed by Pastor *et al.* (2014) and follows the natural variability of river discharge based on the mean monthly flow (MMF). It adjusts the EFRs according to the flow seasons which are separated in high-, intermediate- and low-flow months. The method was developed to increase the protection of freshwater ecosystems during low-flow seasons (when MMF ≤ 40% of mean annual flow (MAF)) and defines for these a reserve of 60% of the MMF. During high-flow seasons (when MMF > 80% of MAF) a minimum flow of 30% is required. Furthermore the method allocates 45% of MMF as EFR during intermediate-flow seasons (when MMF > 40% of MAF and MMF ≤ 80% of MAF) (Pastor *et al.*, 2014).

The second method is based on the Tessmann method which also relies on seasonal EFR variation and therefore distinguishes between high-, intermediate- and low-flow regimes. The main aspect is that water storage during low-flow seasons is more important for the environment as well (Pastor *et al.*, 2014). In low-flow seasons, here also defined as MMF ≤ 40% of MAF, all of the MMF is allocated to the EFRs which means that no water withdrawal is allowed. Jägermeyr *et al.* (2017) adapted this method so that the allocation during low-flow periods is 80% and not 100%. For high-flow seasons (when MMF > 40% of MAF and 40% of MMF > 40% of MAF) a reserve of 40% of the MMF is defined as required amount. For intermediate-flow seasons (when MMF > 40% of MAF and 40% of MMF ≤ 40% of MAF) also 40% of the MMF is allocated to the EFRs (Pastor *et al.*, 2014).

Compared with the first two methods the Smakhtin method does not follow seasonal EFR variation and solely distinguishes between low-flow and high-flow requirements (Smakhtin, Revenga and Döll, 2004). The two key elements of this approach are a minimum baseflow (which is exceeded 90% of the time (Q_{90})) and a percentage of the annual flow (AF). This percentage (h) depends on the mean of the seasonal river flow variability. For stable seasonal flows (Q_{90} > 30% of

AF) only the baseflow is allocated. For higher flow variabilities fractions of the AF (7%, 15% and 20%) are allocated too (Jägermeyr *et al.*, 2017).

Smakhtin *et al.* (2004) defined four potential ecological river statuses which have previously been explained chapter 3. The aim of Jägermeyr *et al.* (2017) was to reach the fair ecological status. The Smakhtin method contradicts the natural flow pattern and therefore has been criticized. Jägermeyr *et al.* (2017) adapted it, hence it allows seasonal variation: the Q_{90} baseflow was replaced by Q_{50} during high flow periods and EFR allocations have been restricted to not exceed 80% of the monthly pristine river flow.

4.2.2 Input data and criticality calculations

Jägermeyr *et al.* (2017) determined the EFRs and withdrawals with the biosphere model LPJmL (Lund-Potsdam-Jena managed Land) which was developed to calculate biophysical and biochemical processes, productivity and yield of the world's major food crops and grazing land. It also simulates transient changes in carbon and water cycles due to land use, phenology and CO_2 fluxes of agricultural-dominant areas at 0.5° resolution (Bondeau *et al.*, 2007). Crop production is represented by 12 specified crop functional types which are rainfed or irrigated. Like the GCWM LPJmL is based on the MIRCA2000 land use data set. The referring time period for the calculations is 1980-2009.

For the calculation of the total withdrawal requirements data for household, livestock production and industrial water uses was taken from Flörke et al. (2013) while LPJmL calculated the irrigation amounts.

The concept of the EFRs was used to allocate the maximum allowed monthly water withdrawals expressed as a percentage of the pristine undisturbed mean monthly river flow (Jägermeyr *et al.*, 2017). This simulation was done without considering human land use, water infrastructure and water withdrawals and was forced with climate data on the simulation period 1980 – 2009. The EFR estimates do not account for fossil groundwater contributions.

The data used in this thesis consists of EFR transgression volumes averaged on a monthly basis over the simulation time period at 0.5° grid cell level. Calculations have been performed on a monthly basis as annual approaches would ignore EFR transgression which occur in the summer months and often are levelled out during the winter time. Two different options have been calculated to cover uncertainties and criticality zones. The first approach defines transgressed and not transgressed grid cells by calculating:

$$\text{Grid cell transgressed} = \frac{Environmental\ flow\ requirements\ (mean\ of\ the\ three\ methods)}{Current\ discharge} > 1$$

It allows to determine all those grid cells which are transgressed at least one month in the year and therefore are critical.

The second approach divides between grid cells which are not critical (transgressed 0 – 1 months during the year), grid cells which are in an uncertainty zone (transgressed 1 - 3 months during the year) and grid cells which are critical (transgressed 3 -12 months during the year).

The EFR transgressions are used to show globally which areas are not in an ecological fair status as defined by Smakhtin. Furthermore, the data was applied to create two criticality maps for each city which combine the blue virtual water imports and the EFR status in the source regions of the imported products.

5 Results

5.1 Blue virtual water imports

The results of this study are calculated as the mean of the years 1998-2002 and show that Berlin imports 56.328.659 m^3 yr^{-1} of blue virtual water related to the 19 analyzed crops (Table 4). Amman on the other hand imports 269.368.276 m^3 yr^{-1}. This demonstrates that Amman's blue virtual water imports are 4.78 times higher than Berlin's.

Additionally, total virtual water imports (blue and green water) have been calculated for the cities. The number totals 2.299.069.093 m^3 yr^{-1} for Berlin and 1.175.017.912 m^3 yr^{-1} for Amman.

Furthermore, the per capita import of blue virtual water of Amman is 141.77 m^3 yr^{-1} which is nine times the amount of Berlin's per capita import which totals 16.09 m^3 yr^{-1}. For further analyzations it is important to also have a look at population sizes and calorie supplies of the cities. From 1998 - 2002, Berlin has an approximate population of 3.5 million and a national average calorie supply of 3338 kcal/day per capita (FAO Food balance sheets) whereas Amman's population is about 1.9 million and its calorie supply amounts to 2777 kcal/day per capita.

Table 4: General information regarding the cities' imports

	Population (million)	**Blue VW import** (m^3 yr^{-1})	**Total VW import** (m^3 yr^{-1})	**Blue VW import per capita** (m^3 yr^{-1})	**National average calorie supply** (kcal/day/capita)
Berlin	3.5	56.328.659	2.299.069.093	16.09	3338
Amman	1.9	269.368.276	1.175.017.912	141.77	2777

5.2 Main source regions

Figures 2 and 3 illustrate the blue virtual water imports and therefore the source regions of Berlin and Amman at a spatial resolution of 5arcmin.

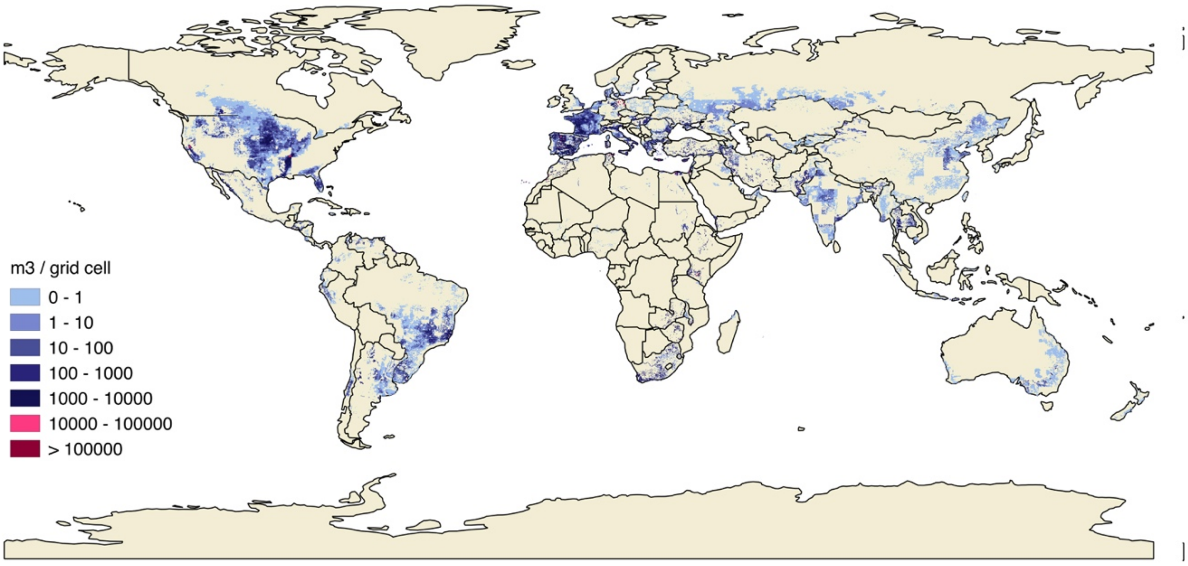


Figure 2: Blue virtual water imports of Berlin

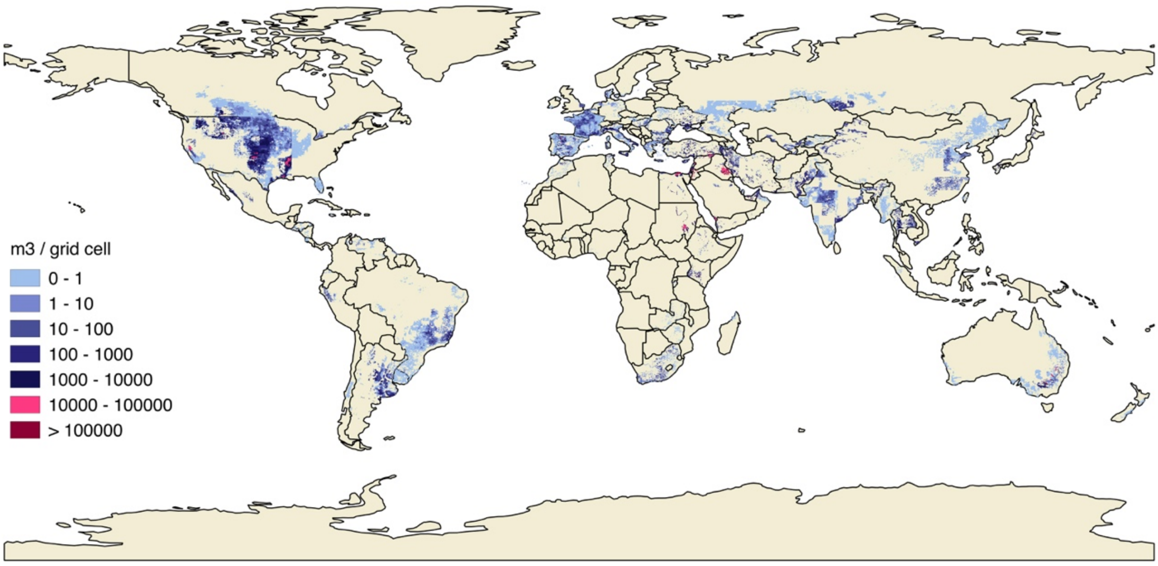


Figure 3: Blue virtual water imports of Amman

Berlin imports most of its blue virtual water from Spain (22.64%), Germany (17.34%) and the USA (16.75%).

Spain presents a very significant source region as many grid cells with high water values (10.000 – 100.000 m^3/grid cell) are located nationwide in the country (Figure 4). Berlin's imports coming from Germany itself have been originated from single hot spots of extremely high grid cells (> 100.000 m^3/grid cell). The hotspots are mainly located in the North-East of Germany (Mecklenburg-Western Pomerania and Brandenburg) and to some extent in the South of Germany (Bavaria) (Figure 5). The USA primarily have a very large export area in the Midwestern region of the country with single high export spots (10.000 – 100.000 m^3/grid cell) (Figure 6).

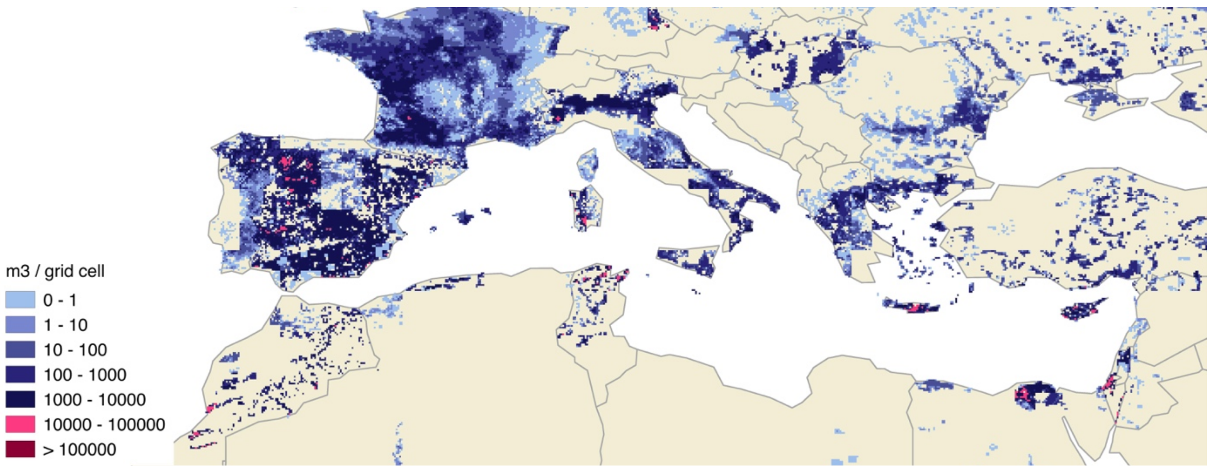
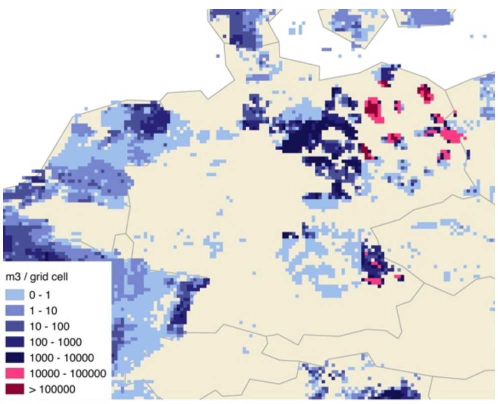


Figure 4: Blue water imports of Berlin (Mediterranean region)



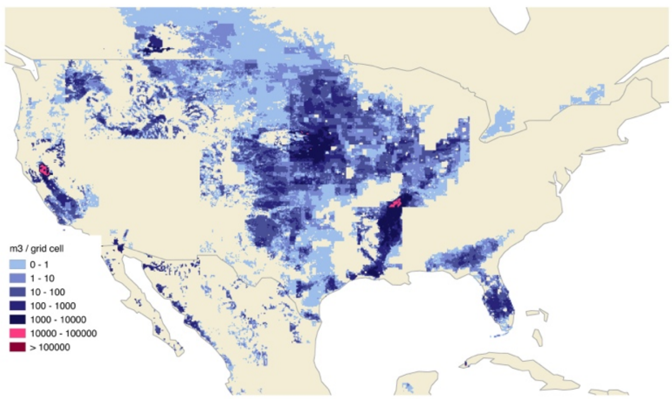


Figure 5: Blue water imports of Berlin (Germany)   Figure 6: Blue water imports of Berlin (USA)

Besides Spain, other important export countries (France, Italy, Greece and Morocco) are located in the Mediterranean region as well (Figure 4). Additional major export nations are Kenya and South Africa. Brazil is the only South American country which largely contributes to Berlin's blue virtual water imports. These countries are the biggest exporters and combine a share of 81.88% on the total blue virtual water imports of the city. A more detailed analysis of the most important source regions is given in Figure 7.

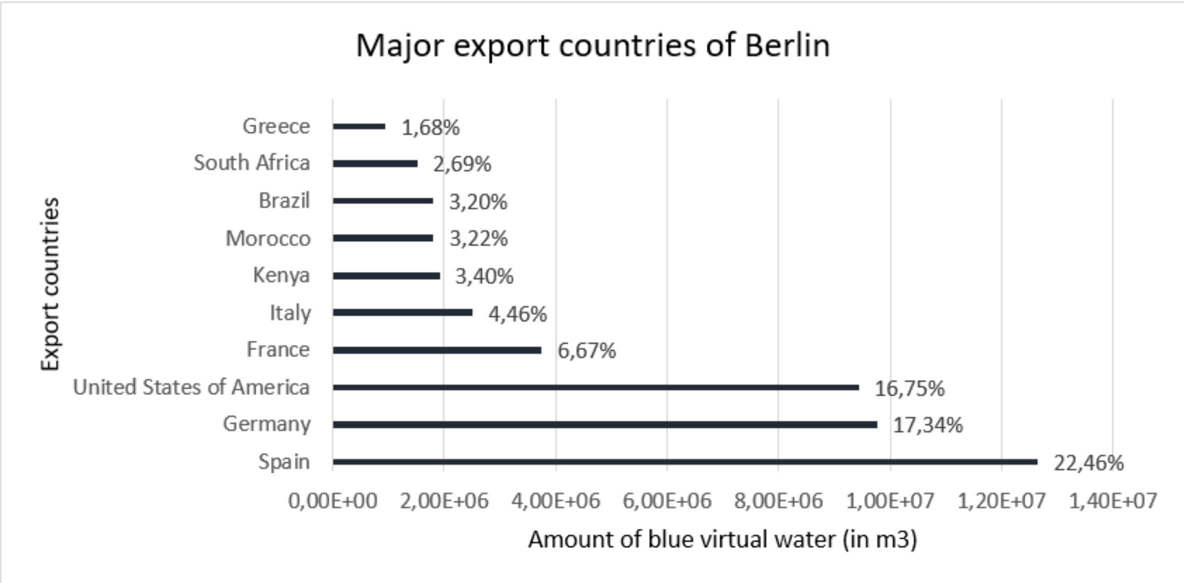


Figure 7: Major export countries of Berlin

Amman imports nearly half of its virtual water from Iraq (46.69%). Another 20.94% come from Jordan itself and 12.59% of the imports come from the USA. Iraq and Jordan have very few but consequently very high export grid cells: > 100.000 m^3/grid cells in Jordan and even > 500.000 m^3/grid cells in Iraq (Figure 8). Amman's imports mostly come from the JRV and partly from the Southern and Northern Badia, as well as the Highlands. The USA is again defined by a large export area with high grid cell amounts (Figure 9).

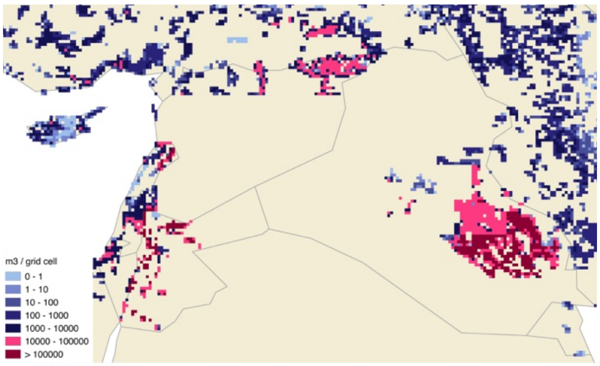


Figure 8: Blue water imports of Amman (Jordan & Iraq)

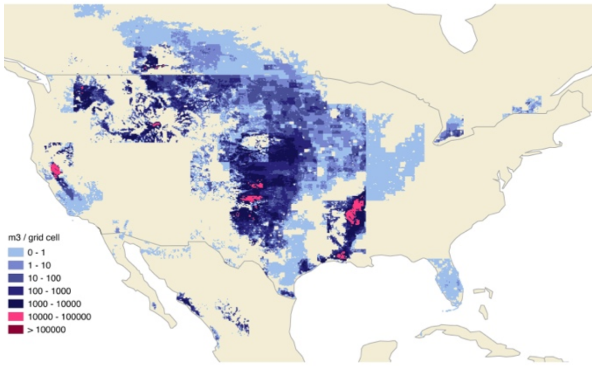


Figure 9: Blue water imports of Amman (USA)

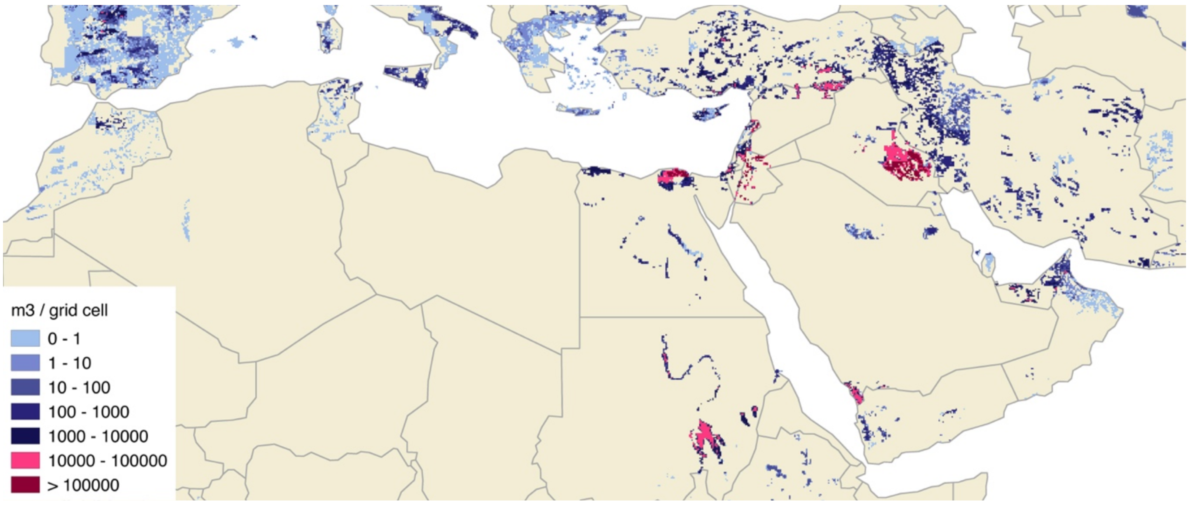


Figure 10: Blue water imports of Amman (MENA region)

Most of the other important export countries of Amman are located in the MENA region: Egypt, the Sudan, Syrian Arab Republic, Israel, Lebanon and in a broad understanding of the MENA region, Turkey (Figure 10). Another important source region is the East Coast of Australia. None of the South American countries are within the major source regions though smaller imports are coming from the Eastern parts of Argentina and Brazil. The mentioned export countries combine a share of 94.42% on Amman's total blue virtual water imports (Figure 11).

The results of this thesis show that both capitals import a large proportion of their products from the own country. The USA are a major exporter to Berlin and Amman as well even though

Amman imports higher values, especially from the Western and Southwestern regions. Furthermore, the numbers reveal that both cities import high water amounts from neighboring countries. Many of Berlins import products come from the EU member states whereas a high share of Amman's products originates from the MENA region.

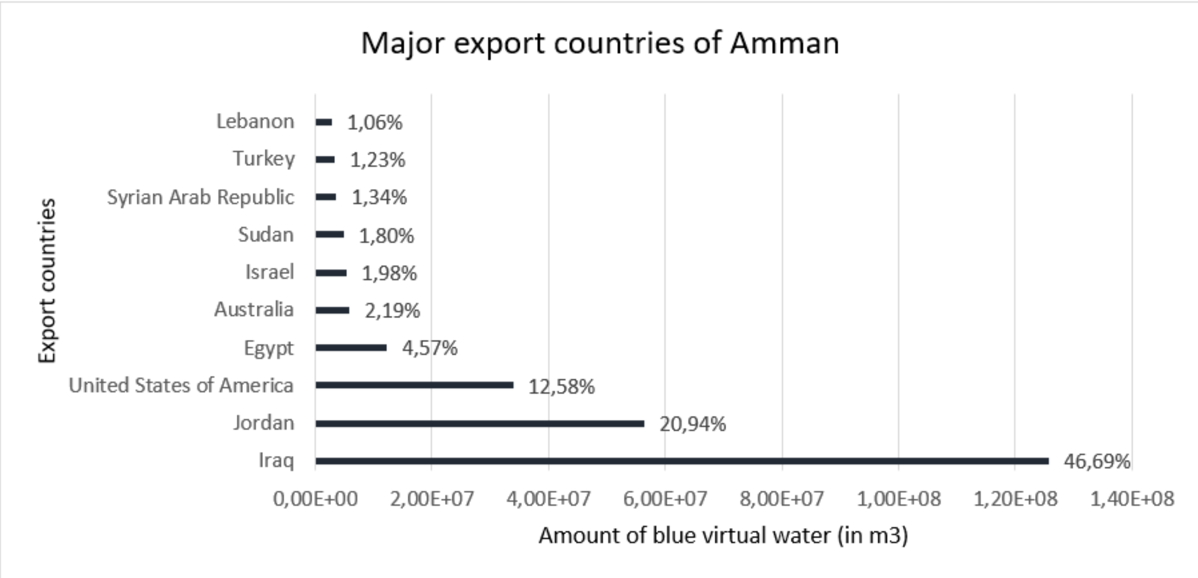


Figure 11: Major export countries of Amman

5.3 Global EFR transgressions

Figure 12 illustrates EFR transgressions based on the assumption that a grid cell is transgressed as long as at least one month in the year is transgressed. The results show that large parts of the Midwest of the USA are exceeded as well as the northern part of Mexico, the Westcoast of South America and areas in the East of Brazil. In Europe, the Mediterranean region, especially Spain is transgressed to a high degree. Furthermore, parts of Western Africa, South Africa and Zimbabwe are under non-ecological EF conditions. The MENA region includes many transgressed regions, especially Turkey, Israel, Afghanistan, Iran and Iraq whereas India shows the most transgressions in one country in the South Asian region. Eastern parts of China and the Australian coast also have many exceeded areas.

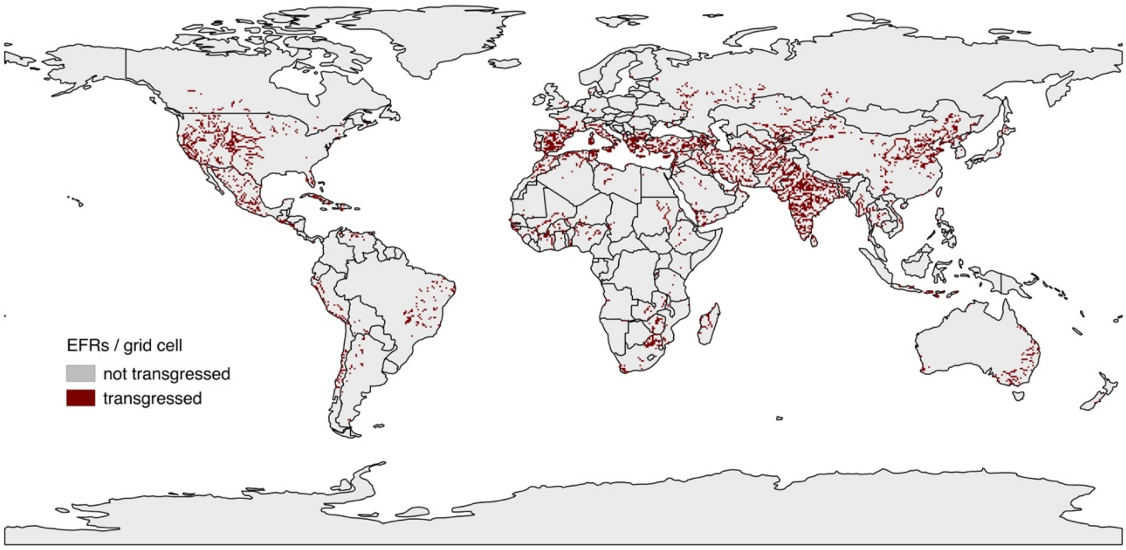


Figure 12: EFR transgressions globally

Figure 12 illustrates a very strict criticality approach which demonstrates at one glance which cells are problematic and which not. However, there are many uncertainties in the methods, models and the general understanding of EFR criticality. To point out that there is not one single understanding of EFR transgression, this thesis also focuses on a more divided approach and defines three criteria which have been explained in chapter 4.

Figure 13 lays out the regions that are not transgressed (0-1 month per year), critical (1-3 months per year) and transgressed (3-12 months per year). The map shows that previously mentioned regions like the Midwest of the USA, Spain, Turkey, India, Pakistan, Afghanistan, China and Australia are still transgressed. Some regions, for instance in the Mediterranean region, the Western USA and Northern Mexico integrate in the critical section now whereas areas in Brazil show many cells that are only transgressed for one month. This differentiation in the criticality results demonstrates that various levels of EFR transgressions exist.

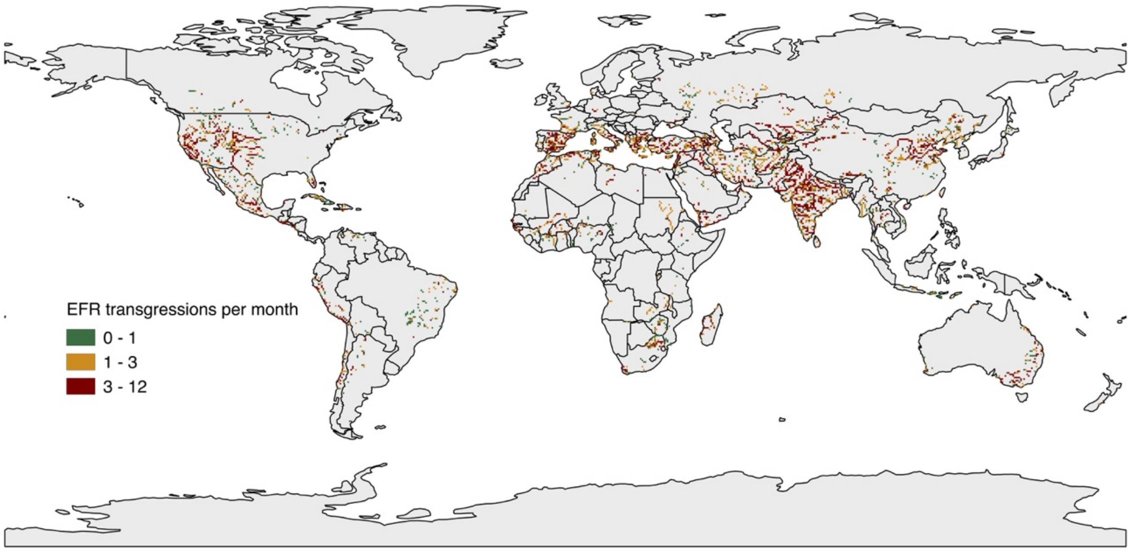


Figure 13: EFR transgressions globally (monthly)

5.4 Criticality maps

One of the main goals of this thesis is to combine the blue virtual water imports of Berlin and Amman with the calculated EFR transgressions to show if the imports come from a region where the EFRs are already transgressed and if yes, to which degree. For each city two maps have been designed to show the previously mentioned criticality definitions. Therefore, import data had to be aggregated to a 0.5° resolution so that both input datasets could be combined.

Figure 14 visualizes that Berlin imports from critical cells especially in the USA, the Mediterranean region, India, the MENA region and parts of China. The amount of blue virtual water imports to Berlin coming from transgressed cells is 29.04%.

Figure 15 gives a more detailed view on the transgressions. Imports stemming from cells which are transgressed 0 – 1 months amount to 15.56% whereas imports coming from cells which are transgressed 1 – 3 months total 39.86%. With 44.46% nearly half of the imports however are originated from cells which are transgressed 3 - 12 months of the year.

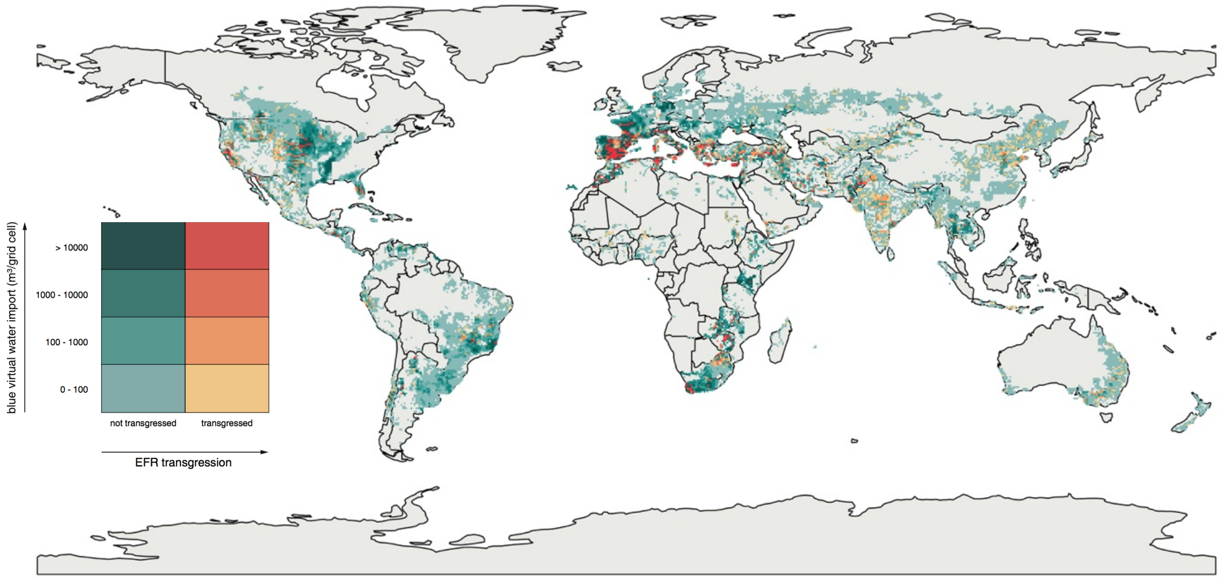


Figure 14: Criticality map of Berlin

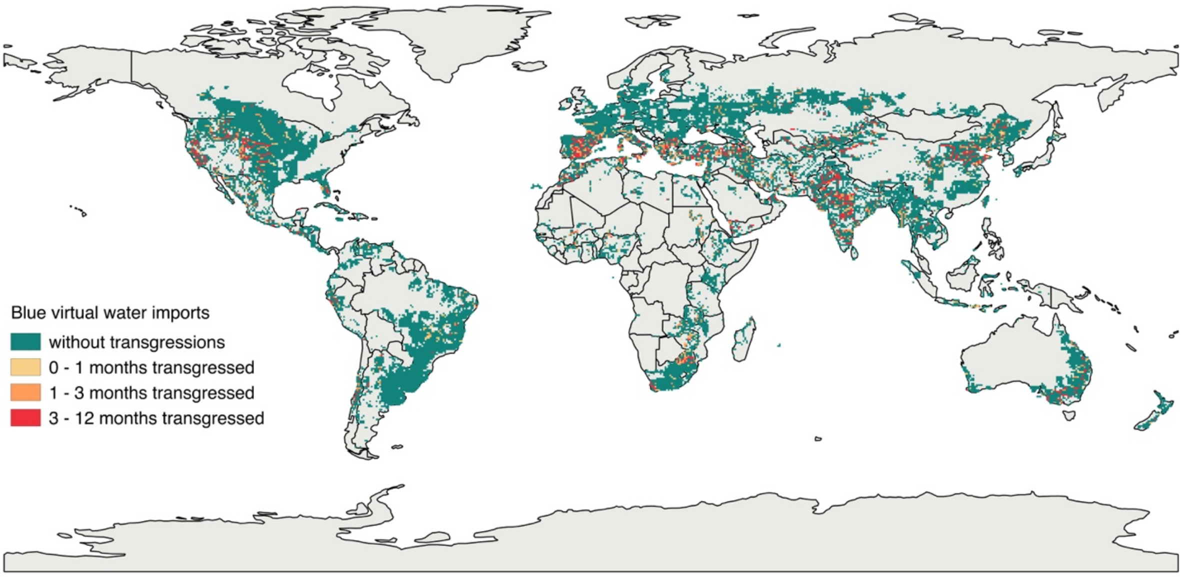


Figure 15: Criticality map of Berlin (monthly)

Amman on the other hand imports 41.44% of its blue virtual water from cells which are transgressed in general. Figure 16 shows that those cells are mainly located in the USA, the MENA region, India, China, Pakistan and Australia.

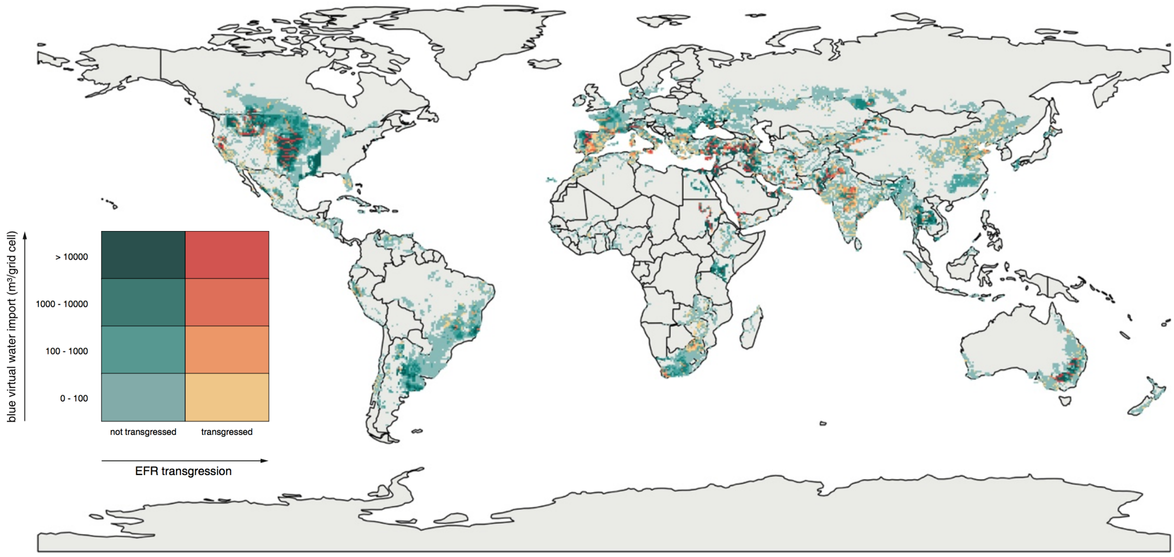


Figure 16: Criticality map of Amman

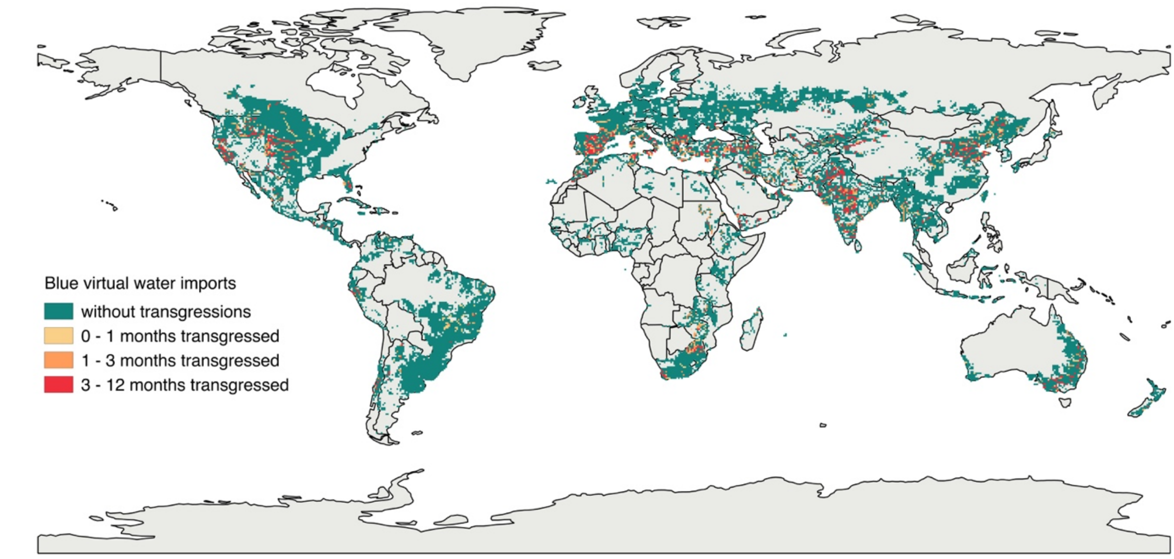


Figure 17: Criticality map of Amman (monthly)

Figure 17 gives a more detailed overview and illustrates that Amman does not only import more water from transgressed cells than Berlin, but also from a higher amount of cells which are transgressed 3 - 12 months (60.34%). Imports from cells which are transgressed 0 - 1 months (19.96%) and 1 - 3 months (19.70%) are nearly the same.

Comparing the criticality maps of Berlin and Amman (Figure 14 and Figure 16) reveals some differences. Amman imports more water from transgressed cells in the USA, the MENA region (especially Jordan, Iraq, Turkey and the Sudan) as well as from the Australian Coast. Berlin on the other hand imports from more transgressed cells in the EU and South America.

However, patterns of the criticality maps (Figure 15 and Figure 17) look relatively similar. To evaluate these patterns an additional map was created visualizing the difference between the criticality maps of both cities. The question arose which of the transgressed import cells are import cells for both cities, only Amman and only Berlin. Figure 18 shows that both cities share a fraction of 88.45% of import cells which totals 2006 cells globally. Berlin furthermore imports from 250 cells alone (11.02%) which are mainly located in Mexico, West Africa, Southern Russia, Kazakhstan and Indonesia. Amman does only import from 12 cells alone globally (0.53%) whereas ten of those cells are located in the MENA region. The difference map illustrates that both cities share a major amount of equal import cells whose EFR are transgressed.

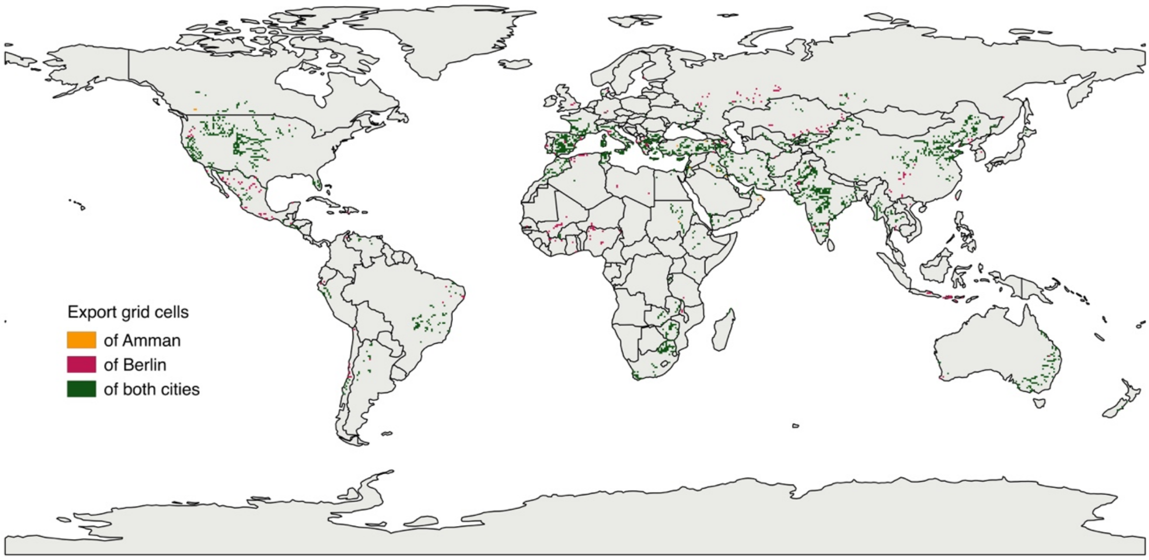


Figure 18: Difference map

6 Discussion

This thesis combines information on crop and therefore blue virtual water imports with a specific criticality of the source regions based on EFR transgressions. As imports are simulated at high spatial resolution (5arcmin) this new approach goes further than many other studies and simulates flows on subnational level – in this case for the cities Berlin and Amman.

The following discussion section focuses on the imports of Berlin and Amman and their source regions. Furthermore, global EFR transgressions and criticality maps will be discussed. The chapter closes with the limitations and uncertainties of this analysis.

6.1 Import structures of Berlin and Amman

First of all, it is necessary to mention that the exemplary comparison of Berlin and Amman presents patterns of a developed and a developing country. On this basis differences in food demand and lifestyle exist.

The results show that Amman imports a higher amount of blue virtual water than Berlin while its population size is smaller. To interpret these results, it is necessary to include the source regions of both cities. Amman imports its crops from many arid and semiarid regions, also Jordan itself is an arid and semiarid country. Thus, the amount of blue water used in Amman's source regions is higher, due to a more intense irrigation. Also, low water use efficiencies and unsustainable water conservation exist in many of Amman's source regions practices as previously outlined in chapter 2.

Moreover, it is important to relate the outcomes to the total virtual water imports which are about twice as high for Berlin. It would be possible that Berlin imports more virtual water in general due to its higher population size and calorie supply.

The numbers also highlight that Amman has a higher share of blue virtual water which is about 22.92% compared to Berlin with only a small share of 2.45%. Antonelli *et al.* (2015) noted that the average ratio of blue water imports of MENA countries regarding agricultural products is around 10% of their total imports. The results do not seem to confirm their observation, albeit it is important to keep in mind that only 19 crops are analyzed in this study. Furthermore, Jordan has to be seen as an extremely water-scarce country highly depending on food imports and therefore having different import patterns than the average countries within the MENA region.

Besides, Berlin's share of blue virtual water could be smaller due to the fact that its source regions are more water-abundant than Amman's. Germany itself is characterized by a temperate and marine climate, therefore growing conditions are very different to those in Amman's source regions. Moreover, the land is less irrigated and higher water use efficiencies occur.

Nevertheless, the BMU (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety) stated that Germany is the largest importer of blue water in the EU (BMU, 2014). The apparently low share of blue virtual water compared to the total virtual water imports might occur because these numbers refer to all imports, not only the 19 crops regarded in this study. It could also show that the amount of blue water compared to green water is very small in general, but nevertheless highly important.

6.2 Comparison of the source regions

The calculation of source regions reveals significant differences between Berlin and Amman regarding the regions and the amount of water exported from there. The only country appearing in the list of major export countries for both cities is the USA who are the biggest virtual water exporter globally with 229 $Gm^3\ yr^{-1}$ (Chapagain and Hoekstra, 2004).

Export grid cells to Berlin in Germany itself are located mainly in Mecklenburg-Western Pomerania, Brandenburg and Bavaria which supports the statement that these federal states are important agricultural producers. Nevertheless, the product flows to Berlin coming from Germany show that the imports do not occur nationwide like for instance in Spain. As Germany is a major agricultural producer in general, more possible export areas would exist theoretically.

It is significant that the majority of the imports for both cities come from many neighboring and surrounding countries. The reason can be found in existing trade structures like the EU which presents an important single market. The results of this study confirm the previous mentioned statement of Serrano *et al.* (2016) that Southern European countries, especially the Mediterranean region are main exporters to Germany. Hereby, Spain is the most important one.

As addressed previously, Amman's export countries are mainly arid and semiarid regions where high amounts of blue water are used for agricultural production. The highest imports originate from Iraq more specifically from the region around Bagdad and Basra where the rivers Euphrat and Tigris run. This region is known as Iraq's main area of cultivation which is very dependent on irrigation. Agriculture is with about 85% the largest water consumer in the country (FAO Investment Centre, 2012) although even some rainfed growing regions in the Northern Iraq exist. Most of Amman's source countries are neighboring countries in the MENA region. This outcome validates the research results of Antonelli *et al.* (2015) who highlighted the major intra-regional component of virtual water exports in the MENA region where 25% of the total exports are addressed towards countries in the same area.

Similar to Berlin, Amman imports high amounts of crops from within the country especially from the JRV but also the Badia and the Highlands. These results show that the most relevant agricultural areas in Jordan are main exporters for its capital.

6.3 Global EFR transgression areas

The results of global EFR transgressions state that areas in the Midwestern USA, Southern Europe, MENA region, Southern Asia, China and Australia are largely transgressed. Those results correlate favorably with the results of blue water footprints of Hoekstra *et al.* (2012b). Especially the rivers Euphrat and Tigris (Turkey, Syria and Iraq) and the Huang He River (China) which refer to a large blue water footprint according to Hoekstra *et al.* (2012b) are very good visible in Figure 12. Moderate transgression results of Mekonnen *et al.* (2016) also correlate with areas in this study including the Mediterranean region, the Western USA and Northern Mexico.

Those areas might be transgressed because they are very important regions for agricultural production. Hence, irrigation values are very high and often not efficient like in Southern Asia (Alexandratos and Bruinsma, 2012) where many transgressed cells can be found. Also, the MENA region shows very large irrigation structures, non-sustainable irrigation patterns and disadvantaged water conservation practices like explained in chapter 2. Those problems combined with the general water scarcity in the region might lead to many EFR transgression cells in the area. In general, EFR transgressions also occur due to high population rates in these regions. In that case more food is needed, and more water for several sectors is used.

The water scarcity and EFR transgression numbers of this study support previous findings in the literature and confirm that specific regions in the world are very water-scarce partly due to the reasons listed above. The trade of virtual water is not sufficient to change these shortages. It might relieve a country like Jordan on the one hand as its capital Amman is able to import many products from outside the country borders. But on the other hand, the complexity of water flows shifts the problem to countries like Iraq, Egypt and Australia that also have to deal with water scarcity. In the case of Berlin countries like Spain and France as well as the Western parts of the USA struggle with more water shortages.

6.4 Analysis of the criticality maps

Figure 16 and Figure 17 visualize that Jordan imports more water from critical cells than Berlin. In addition, Jordan also imports more water from cells which are extremely transgressed (in average 3 – 12 months per year) than Berlin. This result might point to the fact that Amman imports water from more arid and semiarid regions and is more dependent on blue water than Berlin is. Berlin's share of blue water is with 2.45% quite small compared to Amman. The fact that Amman also imports high amounts from Jordan itself seems to be in contradiction with the extreme water scarcity in the country.

This begs the question whether a water-scarce country like Jordan and therefore also Amman should import more food from water-abundant countries and not export agricultural products on its own to save water for domestic purposes, industry and environment. It must be asked why countries do not make more use of the virtual water trade if it seems to be a suitable solution for many water-scarce regions.

One reason might be that the production of export goods can be very important for the national economy like in Jordan where many people are salaried in the agricultural sector and its downstream activities which leads to a contribution of that area to 29% of the national GDP (Abu-Sharar, Al-Karablieh and Haddadin, 2012). However, sometimes the economically positive export takes place at the expense of additional pressure on the nation's blue water resources if much irrigation occurs which is the case in a country like Jordan.

But, as previously explained in the basic concepts, the market does not follow water scarcity calculations. The results of the criticality maps rather confirm the statement of De Fraiture *et al.* (2004) that the potential of virtual water to relive water-scarce countries in reality is modest. Virtual water does not flow only because countries want to save domestic water resources. International trade in agricultural goods is reliant on much more factors like the availability of land, labor, knowledge, the existence of domestic subsidies, import taxes etc. (Hoekstra, Arjen Y. and Chapagain, 2008). Furthermore, small income economies do not play an important role in the global market as already stated by Yang *et al.* (2006).

Also, many imports of Berlin come from water-scarce countries whereas most regions in Germany itself are water-abundant. The question arises why 29.04% of the imports to Berlin therefore come from transgressed cells. However, also in this case the market does not pay much attention to EFR transgressions.

The nonexistent contrasts in the difference map (Figure 18) regarding different export grid cells for both cities might exist due to the fact that the GCWM reaches its limits in the distribution of the export grid cells. As previously mentioned the model does not distinguish between real and feasible surplus cells in the source regions, therefore it seems possible that the export cells of a specific country exporting to Berlin and Amman are similar if both cities trade with this specific country. The results show that further adjustment is necessary to better define source grid cells and therefore the imports' share on transgressed areas.

The share of Berlin and Amman on imports from critical areas has also to be discussed considering what actually defines criticality. Is a share of about 41.44% high or becoming more normal nowadays where the world's population increases and more food is needed? The question arises if it would be best to furthermore import from transgressed areas or whether water-abundant and rich countries like Germany should pay more attention to their source regions. In the end exports from critical regions to other parts of the world might not be the only reason for EFR transgressions, but are an important factor, still.

The interpretation of the criticality maps also poses the question what meaning large water exports have for the source regions. On the one hand, agriculture might be an important sector which provides a basis for labor, economy and living standards. Therefore, the exports could be positive for the source regions. On the other hand, these exports might not have only a major ecological, but also social and political impact. Through globalized trading structures, arable land is often bought by large companies. Therefore, the control of water can shift from local communities which often rely on the resource to multinational agribusinesses. Virtual water exports might also worsen local food sovereignty and therefore have considerable social and political risks. Within the context of this study impacts on social and political levels cannot be discussed. However, they are of great importance for the evaluation of virtual water trade.

The results of this study need to be interpreted with caution as they do not determine the extent of responsibility the cities have regarding the EFR transgressions and water scarcities in the source regions. It only illustrates that the cities import from different areas and whether those areas do fulfill the EFRs or not.

Other authors like Lenzen *et al.* (2013) analyzed blue water footprints and virtual water flows combined with water scarcity. This scarcity-weighted approach shows that net importers of water are developed and water-abundant economies which import the largest parts of scarce water at the same time. Unlike the mentioned approach, this study does not weight scarcity.

6.5 Limitations and uncertainties

It is plausible that a number of limitations regarding the GCWM and the applied algorithm might have influenced the results obtained. First, no processed products have been considered, as for instance soybean processed into soybean flow and soy bean oil. As a consequence, important final goods could not be analyzed regarding further water uses in their processes of production. Another disadvantage of the methodology would be that different diets and calorie compositions of varying countries are not taken into consideration. Further data would be required to determine exactly how the diet of an average Berlin citizen is composite compared to a citizen of Amman.

An additional major source of uncertainty in the method used is due to the fact that the GCWM does not define real export grid cells. The algorithm determines a set of surplus cells in a country which are used for the international export of goods, but whether surplus cell A or cell B exports to Berlin is not defined. Hence, grid cells and explicitly exported amounts are chosen arbitrarily, falsifying the results obtained. To improve the results a bottom-up analysis is needed which would be time and data intensive. Such an approach was adapted by Flach *et al.* (2015) who collected data from Brazilian municipalities regarding virtual water trade flows by assigning high-resolution water footprints of two products to spatially-explicit material trade flows.

While interpreting the results it is also important to mind that the water intensive crop cotton is not included in the analysis. During 1997 – 2001 the virtual water flows between nations regarding international trade in cotton products amounted to 204 $Gm^3 yr^{-1}$ whereas about 43% of this flow has been blue virtual water (Chapagain *et al.*, 2005). In relation to the international trade of crop, livestock and industrial products cotton trade had a share of about 12% during the time period analyzed and would therefore have major impacts on blue virtual water flows and EFR transgressions. As previously mentioned, the 19 analyzed crops cover an area of 71% of the globally harvested cropland (Hoff *et al.*, 2014). Hoekstra *et al.* (2004) determined the virtual water trade of the years 1997 – 2001 for crop, livestock and industrial products and calculated that 61% of the international trade was related to crops and crop products. Taken these numbers into account, the results of this study are nevertheless relevant for the analyzed time period.

As the focus of this study is on blue water it is conceivable that dissimilar evaluations would have arisen if the focus had been on green water too. In order to compare the numbers with EFR data it was important to focus on blue water. Furthermore, green water in the soil cannot be used in many different ways and is always a consumptive use of freshwater (Rockström *et al.*, 2009a) whereas blue water is also the source for households, industry and livestock and therefore could be considered as more valuable.

Regarding EFR transgressions and water withdrawals in general, this study neglects downstream effects of grid cells. This implies that the impact one grid cell transgression can cause in another grid cell is not covered in this analysis. By having a look at e.g. Russia in Figure 12, it is obvious that many single cells are transgressed in the South. This study does show that they are transgressed but does not further investigate the reason for that.

It is furthermore important to mention that the GCWM and LPJmL are not consistent regarding their input data and calculation methods. Therefore, it is necessary to note the study's results have to be interpreted cautiously.

The analysis points out where the source regions of Berlin and Amman are but does not answer the question to which degree the cities' exports contribute to EFR transgressions in these regions. First, the impact of the cities is very small and second, this analysis is performed with consumptive water use data solely, so no total withdrawals are taken into consideration which might underestimate the effect on the EFRs. For calculating a *responsibility* of the cities further data, together with a weighted scarcity approach and global data for trade flows and additional processes would be necessary.

7 Conclusion

This bachelor thesis outlines blue virtual water imports of the cities Berlin and Amman. Significant differences have been found between both cities. Amman imports a 4.78 times higher amount of blue virtual water than Berlin, whereas Berlin's total virtual water imports are with 2.3 km^3 yr^{-1} about twice of Amman's total imports. Furthermore, the analysis revealed that neighboring countries are major export regions for both capitals, as well as the own country and the USA. While Berlin imports 29.04% from transgressed cells and 44.46% % from cells that are transgressed 3 -12 months, Amman's share is higher. 41.44% of the products come from transgressed cells and even 60.34% from 3 – 12 months exceeded cells.

The work has led to the conclusion that Amman's higher share on blue virtual water has many reasons. First of all, the higher share of blue water of Amman is partly due to the general extreme water scarcity in the country and consequently the dependency of Jordan on food imports. Secondly, the imports are originated mainly from arid and semiarid source areas in the MENA region where irrigation values are high, though irrigation efficiencies and water conservation practices non-sustainable. This is also an approach to answer the question why Amman imports more water from transgressed cells than Berlin. Still, a definite answer could not be provided.

The thesis confirmed previous studies defining water-scarce regions where EFRs are transgressed globally and shows similar patterns. Furthermore, the analysis states that virtual water trade could have a very positive effect but does not advantage all water-scarce nations. Agriculture is a very important sector for Germany and Jordan, but while Germany is an important economy in the globalized market and imports most of its products from the EU single market, Jordan solely plays a small role.

The strength of this analysis is the development of two criticality maps. Consequently, this thesis combined in a new approach virtual water flows and EFR transgressions of the imports' source regions on a subnational level. However, many limitations regarding models and data used occurred and need to be taken into consideration.

To meet the growing food demands of the world population while sustaining on the other hand ecosystems will be a major challenge for the next decades. Water-scare countries like Jordan need to change their cropping patterns, cultivate less water-intensive crops and pay attention to their precious blue water resources (Abu-Sharar, Al-Karablieh and Haddadin, 2012). Virtual water trade could be a part of the solution albeit, attention has to be paid not to only shift water availability problems to other water-scare regions. A complex hydrological, technological and political solution has to be found. Therefore, water productivities in agricultural production will have to increase globally. The focus has to be on the establishment of rainfed agriculture where the integration with rainwater management could achieve global profits of 10% regarding agricultural production (Jägermeyr *et al.*, 2017). Furthermore efficiencies of existing irrigation systems have to be improved especially in water-scarce areas like the MENA region where irrigation efficiency could raise up to 9% (Alexandratos and Bruinsma, 2012).

An increasing understanding of water footprints and the concept of virtual water trade is necessary. The responsibility of water use is distributed over the entire supply chain of products and not solely lies with the producers or consumers. However, the picture of blue virtual water imports of cities is still incomplete. For a further analysis imports of more and more diverse products, also all cities in the world would have to be determined to capture the complex image as a whole.

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Supplementary Material

Grid cells of Berlin and Amman

Grid cells of Berlin have been taken from Hoff *et al.* (2014). Grid cells of Amman were specifically calculated for this thesis form the GCWM.

Table 5: City specific grid cells

Cell number	**Berlin**		**Amman**	
	Latitude	Longitude	Latitude	Longitude
1	52.6250	13.2917	31.87500	35.87500
2	52.6250	13.3750	31.87500	35.95833
3	52.6250	13.4583	31.95833	35.79167
4	52.5417	13.1250	31.95833	35.87500
5	52.5417	13.2083	31.95833	35.95833
6	52.5417	13.2917	32.04167	35.79167
7	52.5417	13.3750	32.04167	35.87500
8	52.5417	13.4583	32.04167	35.95833
9	52.5417	13.5417	32.04167	36.04167
10	52.5417	13.6250		
11	52.4583	13.1250		
12	52.4583	13.2083		
13	52.4583	13.2917		
14	52.4583	13.3750		
15	52.4583	13.4583		
16	52.4583	13.5417		
17	52.4583	13.6250		
18	52.4583	13.7083		

Exemplary R Script of Amman

This main R script visualizes how import values, source regions and criticalities have been calculated. Reclassifications of the data also have been performed in QGIS directly and are therefore not displayed here. The main script for the EFR input data was provided by Fabian Stenzel.

```
### calculation of the mean (1998-2002)

   dataAbluetot_1998 <- raster("VWS_BLUE_TOT_1998.ASC")
   dataAbluetot_1998.df <- as.data.frame(dataAbluetot_1998, xy = TRUE)

   dataAbluetot_1999 <- raster("VWS_BLUE_TOT_1999.ASC")
   dataAbluetot_1999.df <- as.data.frame(dataAbluetot_1999, xy = TRUE)

   dataAbluetot_2000 <- raster("VWS_BLUE_TOT_2000.ASC")
   dataAbluetot_2000.df <- as.data.frame(dataAbluetot_2000, xy = TRUE)

   dataAbluetot_2001 <- raster("VWS_BLUE_TOT_2001.ASC")
   dataAbluetot_2001.df <- as.data.frame(dataAbluetot_2001, xy = TRUE)

   dataAbluetot_2002 <- raster("VWS_BLUE_TOT_2002.ASC")
   dataAbluetot_2002.df <- as.data.frame(dataAbluetot_2002, xy = TRUE)



   sum1998to2002_Amman <- overlay(dataAbluetot_1998A,
                          dataAbluetot_1999A,
                          dataAbluetot_2000A,
                          dataAbluetot_2001A,
                          dataAbluetot_2002A,
                          fun=function(r1, r2, r3, r4, r5){return((r1+r2+r3+r4+r5)/5)})



### aggregation of the data (from 5arcmin to 0.5°)

   dataAbluetot_1998_agg <- aggregate(dataAbluetot_1998, fact=6, fun=sum)
   dataAbluetot_1999_agg <- aggregate(dataAbluetot_1999, fact=6, fun=sum)
   dataAbluetot_2000_agg <- aggregate(dataAbluetot_2000, fact=6, fun=sum)
   dataAbluetot_2001_agg <- aggregate(dataAbluetot_2001, fact=6, fun=sum)
   dataAbluetot_2002_agg <- aggregate(dataAbluetot_2002, fact=6, fun=sum)

   sum1998to2002_Amman_agg <- overlay(dataAbluetot_1998_agg,
                              dataAbluetot_1999_agg,
                              dataAbluetot_2000_agg,
                              dataAbluetot_2001_agg,
                              dataAbluetot_2002_agg,
                              fun=function(r1, r2, r3, r4, r5){return((r1+r2+r3+r4+r5)/5)})
```

calculation of the source regions

```
    ıtries <- raster("iso_cr.asc")
  countries.df <- as.data.frame(countries, xy = TRUE)

  water_imports_Amman <- sum1998to2002_Amman

  water_countries_Amman <- stack(countries, water_imports_Amman)
  water_countries_Amman.df <- as.data.frame(water_countries_Amman, xy = TRUE)

 water_countries_Amman_imports.df <- subset(water_countries_Amman.df, water_countries_Amman.df$layer
>0)

  # calculation of countries' water content
    aggregated_Amman.df <- aggregate(water_countries_Amman_imports.df$layer,
    by=list(Category=water_countries_Amman_imports.df$iso_cr), FUN=sum)
```

###EFR calculations

```
  require(ncdf4)
  nc <- nc_open("fraction_of_EFR_and_discharge_1981_2010.nc",readunlim=FALSE)
  array1 <- array(0,dim=c(720,360))
  var <- nc$var[[1]]
  array1 <- ncvar_get( nc, var,   start=c(1,1,9), count=c(720,360,1))
  nc_close(nc)

  require(raster)
  r <- brick("fraction_of_EFR_and_discharge_1981_2010.nc")

  january <- r[[1]]
  february <- r[[2]]
  march <- r[[3]]
  april <- r[[4]]
  may <- r[[5]]
  june <- r[[6]]
  july <- r[[7]]
  august <- r[[8]]
  september <- r[[9]]
  october <- r[[10]]
  november <- r[[11]]
  december <- r[[12]]

  #calculations binary
  maxEFR <- calc(r, max)
  fun1 <- function(n) ifelse(n>1, 1, 0)
  EFRbinary <- calc(maxEFR, fun1)

  #calculations monthly
  fun1 <- function(n) ifelse(n>1, 1, 0)

  janbinary <- calc(january, fun1)
  febbinary <- calc(february, fun1)
  marbinary <- calc(march, fun1)
  aprbinary <- calc(april, fun1)
```

```
  maybinary <- calc(may, fun1)
  junbinary <- calc(june, fun1)
  julbinary <- calc(july, fun1)
  augbinary <- calc(august, fun1)
  sepbinary <- calc(september, fun1)
  octbinary <- calc(october, fun1)
  novbinary <- calc(november, fun1)
  decbinary <- calc(december, fun1)

  allmonthbinary <- sum(janbinary, febbinary, marbinary, aprbinary, maybinary, junbinary, julbinary, augbinary,
 sepbinary, octbinary, novbinary, decbinary)
  allmonthsbinary_df <- as.data.frame(allmonthbinary)



###criticality map reclassifications

  #binary
   rcla_Amman <- c(0, 100, 120, 100, 1000, 130, 1000, 10000, 140, 10000, 1000000000, 150)
   sum_Amman_reclassified <- reclassify(sum1998to2002_Amman_agg, rcla_Amman,
   filename='CM2_Amman_imports_reclassified.tiff', include.lowest=FALSE, right=TRUE)


  #monthly
   rcla_Amman_months <- c(0.0000000001, 100000000, 100)
   sum_reclassified_Amman_months <- reclassify(sum1998to2002_Amman_agg, rcla_Amman_months,
   filename="CM2_Amman_reclassified_months.tiff", include.lowest=FALSE, right=TRUE)



###criticality map calculations binary

  water_Amman <- raster("Amman_Imports_1998to2005_0.5.tif")
  critical_map_Amman <- raster("Criticality_map_Amman_binary.tif")

  water_critical_Amman <- stack(water_Amman, critical_map_Amman)
  water_critical_Amman

  water_critical_Amman_df <- as.data.frame(water_critical_Amman, xy = T)
  table(water_critical_Amman_df$Criticality_map_Amman_binary)

  #second reclassification

 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 20] <- 1
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 30] <- 2
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 40] <- 3
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 50] <- 4
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 60] <- 5
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 21] <- 6
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
 _binary == 31] <- 7
 water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
```

```
_binary == 41] <- 8
water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
_binary == 51] <- 9
water_critical_Amman_df$Criticality_map_Amman_binary[water_critical_Amman_df$Criticality_map_Amman
_binary == 61] <- 10

water_critical_Amman_df2 <-
subset(water_critical_Amman_df,water_critical_Amman_df$Criticality_map_Amman_binary <6)



#criticality map calculations monthly

  water_Amman <- raster("Amman_Imports_1998to2005_0.5.tif")
  critical_map_Amman_months <- raster("Criticality_map_Amman_months.tif")

  water_critical_Amman_months <- stack(water_Amman, critical_map_Amman_months)
  water_critical_Amman_months

  water_critical_Amman_months_df <- as.data.frame(water_critical_Amman_months, xy = T)

  #second reclassification

 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 0] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 1] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 2] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 3] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 4] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 5] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 6] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 7] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 8] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 9] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 10] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 11] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 12] <- 1
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 100] <- 2
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 101] <- 3
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 102] <- 4
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
 ality_map_Amman_months == 103] <- 4
 water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
```

```
ality_map_Amman_months == 104] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 105] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 106] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 107] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 108] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 109] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 110] <- 5

water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 111] <- 5
water_critical_Amman_months_df$Criticality_map_Amman_months[water_critical_Amman_months_df$Critic
ality_map_Amman_months == 112] <- 5


    water_critical_Amman_months_df3 <- subset(water_critical_Amman_months_df,
    water_critical_Amman_months_df$Criticality_map_Amman_months ==3)
    water_critical_Amman_months_df4 <- subset(water_critical_Amman_months_df,
    water_critical_Amman_months_df$Criticality_map_Amman_months ==4)
    water_critical_Amman_months_df5 <- subset(water_critical_Amman_months_df,
    water_critical_Amman_months_df$Criticality_map_Amman_months ==5)


#calculations difference map
 difference_map <- raster("Difference_map.tif")
 difference_map_df <- as.data.frame(difference_map, xy = TRUE)

 difference_map_3_df <- subset(difference_map_df, difference_map_df$Difference_map ==3)
 difference_map_6_df <- subset(difference_map_df, difference_map_df$Difference_map ==6)
 difference_map_18_df <- subset(difference_map_df, difference_map_df$Difference_map ==18)
```

Declaration of academic honesty

I hereby declare that the present thesis has not been submitted as a part of any other examination procedure and has been independently written. All passages, including those from the internet, which were used directly or in modified form, especially those sources using text, graphs, charts or pictures, are indicated as such. I am aware that any breach against these rules is considered as plagiarism and will be punished according to the general university regulations (Allgemeine Satzung zur Regelung von Zulassung, Studium und Prüfung Humboldt-Universität zu Berlin, ZSP-HU).

Dahlmann

Berlin, 27.06.2018 Heindriken Margarete Dahlmann