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Master Thesis

“Reassessment of the role of industrial water demand in global monthly water stress, for the year 2000”

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Abstract

Presently only 10% of maximum available blue water resources, is used by the three consumptive categories, the agricultural, the industrial and the domestic. Recent studies have showed that water demand is expected to increase within the next decades due to constantly growing population, whereas the available freshwater resources are not likely to increase with the same rate and this makes the appropriate management of freshwater resources urgent. This study assessed the amount of pressure put on available blue water resources by using the Water Scarcity Index. The monthly water demand for the year 2000 as benchmark year was calculated and was contrasted against 44 years (duration: 1958-2001) of a long-term climate based on ERA-40 and CRU TS 2.1 meteorological data sets. We also estimated for the year 2000 the additional fresh water resources (e.g. desalinated water use and groundwater abstraction).

The results of this study indicate that about 1.67 to 2.27 billion people live under moderate to high water stress but it is subject to change, depending on whether we are looking at a monthly or a yearly temporal resolution. Our results compared to the results of other studies, showed that about 0.21 billion less people live under moderate to high water stress. This could practically mean that past studies overestimated the amount of people living under moderate or high water stress.

This assessment also revealed those regions globally, which in the year 2000 experienced high water stress. In January the regions which suffer from high water stress (WSI>0.4) are located mostly in parts of North India, East Australia, Central Asia and Central Africa. The situation in February stays the same but regions in Southern India, West Australia and East Asia show the same behavior like the rest regions in January. March and April are months that high water stress occurs in the western parts of India, East China and Central Africa. Western parts of North America deal with high water stress in several months of year 2000 (May, June, July and August). In the summer months (June to September in the Northern Hemisphere and December to March in the Southern Hemisphere) regions located around Mediterranean Sea (Spain, Italy, Greece, Algeria and Morocco), North India, Pakistan and East China face high water stress conditions. In the rest months of the year the problem of high water stress is visible in South Africa, central parts of South America, East Europe and East Asia (regions in China and Mongolia).

Keywords: *Water demand; Industrial water demand; Blue water availability; Water stress; Water scarcity; Water Scarcity Index*

1. Introduction

1.1. Background and problem description

Water scarcity, mostly nowadays but also in the past, has been one of the most pressing environmental issues in the world. It occurs when and wherever the renewable freshwater resources cannot meet the water demand. Previous studies on available freshwater resources and water demand (Rosegrand et al., 2002) have showed that water demand is expected to increase within the next decades due to constantly growing population, whereas the available freshwater resources are not likely to increase with the same rate and this in combination with the fact that water is the driving force in many aspects of the human societies makes the appropriate management of freshwater resources urgent.

Even though the 70% of the earth is covered with water, only about a 2.5% out of it is renewable freshwater. Renewable freshwater resources are partitioned into blue and green water. According to Oki and Kanae (2006), evapotranspiration flow has been named green water, and conventional withdrawal from rivers and groundwater has been named blue water. Presently only 10% of maximum available blue water and 30% of green water resources are used by the three consumptive categories, the agricultural, the industrial and the domestic (Oki and Kanae, 2006). The factors that control the availability of renewable freshwater resources are mostly climate variability but also humans. For a case study in west Africa, Ojo et al. (2004) claim that in the forest areas in the southern part of west Africa rainfall is spread over many months, whereas in the inland areas (northern parts of west Africa) the rainfall, which is low, is spread over 3-4 months. This climate variability results in small rivers to fall away rapidly after rain periods and cease during dry seasons in the northern parts and in the southern parts, small rivers to be able to sustain permanent flow during dry seasons which in reality means that in some cases humans often need water when it is least available and in other cases there is an excess of water availability even though it is not needed (Ojo et al., 2004; Hua et al., 2007). Humans can affect the availability of renewable freshwater resources but also their temporal variability with construction of reservoirs. Adam and Haddeland (2007) suggest that the construction and operation of large reservoirs result in a shift in stream flow seasonality, which reduces spring and summer peak flows and increases fall and winter low flows. Besides their temporal variability, available water resources also vary significantly in space. Brazil, the Russian Federation, Canada, the United States of America (U.S.A.), the People's Republic of China (PRC) and India have more than 40% of the global annual river runoff formed within their territories (Shiklomanov, 1998). River runoff is also unevenly distributed within the territories of these countries.

When the local available water resources cannot meet the local water demand, then additional freshwater resources are needed in order to meet the local water demand and cover the different needs of the people. Thus in many cases two additional freshwater resources are added to the blue water availability, the desalinated water use and the groundwater abstraction. These two water resources are part of the total water demand but their source is sea water and groundwater, respectively

Similar to water availability, water demand varies both in space and in time. For example growing urban population causes a higher water demand at a particular geographic location. Water demand is mostly controlled by two factors and these are the population growth and the development of a country. As the population of a country increases the water demand also increases in order to cover the different needs of the population (food, energy, sanitation). Solley (1997) states that from 1960 to 1975, an increase of 20% in the population in the western United States of America, resulted in an increase of 35% in the total water demand. The development of a country results in an increase of water demand; Kumar (2006) claims, that the water demand in developing countries is quite low in comparison to developed countries. This spatiotemporal variability of both available water resources and water demand leads different regions to experience different degrees of water stress at different times (Wada et al., 2011b).

Therefore the largest issue is to quantify the imbalance of water availability and water demand which results in water scarcity throughout the year but also between the years. So far approaches to describe water stress, mostly work at a yearly temporal resolution which means that they are not able to grasp the characteristics of water stress such as timing, duration, intensity and magnitude over the year. Thus the use of shorter temporal resolution is necessary because it enables detailed assessments considering the effects of spatiotemporal variability in water demand and available freshwater resources. In the recent years Wada et al. (2011a), Hanasaki et al. (2008a, 2008b) and Hoekstra et al. (2012) were the first that used a finer temporal resolution in their assessments (e.g. month).

It is important to separate water demand in terms of purpose (industrial, agricultural and domestic), something that will allow us to treat each sector of interest differently and therefore assess water stress in a more detailed manner, like it has been introduced in previous assessments (Wada et al., 2011a) and additionally highlight regions where the competition of the different components of water demand is high, leading to water stress.

1.2. Previous Work on the Global Water Scarcity

1.2.1. Historical Development

The first studies concerning water availability and water demand were conducted back in the 1970 and they were done mainly on a regional scale. Ledger (1972) was one of the first who conducted such a study of water availability and water demand for the Warwickshire Avon area in England, United Kingdom. After these regional assessments of water stress, due to the fact that the imbalance of water availability and water demand has emerged over the past decades in different regions of the world, scientists promoted such studies on a global scale (Vörösmarty et al., 2000; Oki et al., 2001; Arnell, 2004; Alcamo et al., 2003; Wada et al., 2011). This major issue has been attracting the attention of the scientists more and more and over the past decade the efforts to conduct studies regarding water availability and water demand have increased in a high degree (Smakhtin et al., 2004).

Global water stress assessments were initially introduced to the scientific community by Falkenmark (1989), by contrasting the available freshwater resources against the population size. In the following years the water scarcity index (WSI) or 'water withdrawal to water availability ratio' as it was defined by Alcamo et al. (2003), was widely used in different assessments (Alcamo et al., 2003; Oki and Kanae, 2006; Vörösmarty, 2000; Wada et al., 2011) in order to identify the different degrees of water stress both on a regional and a global scale. According to Oki and Kanae (2006) the water scarcity index is the ratio between the annual water withdrawals by all the three sectors, minus the water generated by desalination and groundwater abstraction, to the renewable freshwater resources:

$$Rws = \left(W - S\right) / Q, \qquad (1.1)$$

where Rws is the water scarcity index (-), W is the annual water withdrawal by all the sec- tors, S is water generated by desalination and groundwater abstraction and Q is the renewable freshwater resources.

Falkenmark (1989) was the first who promoted the concept of a threshold value of water stress in order to describe the different degrees of water scarcity that various regions of the world experience. Later, Raskin et al. (1997), Vörösmarty et al. (2000), Alcamo et al. (2000, 2003) and Wada et al. (2011) all used in their assessments a threshold value of 0.4 which represents 'high' or 'severe' water stress. According to Alcamo et al. (2003) areas in this category include most of India, northern China, middle Asia, the Middle East, northern and southern Africa, parts of southern Europe, western Latin America, a large part of the western United States, northern Mexico, and a few river basins in Australia. It is considered to be a reasonable, although not definitive, threshold value because not all the renewable freshwater resources can be used by humans.

The imbalance of water availability and water demand results in water stress and more specifically it occurs when the local demand exceeds local water availability. As mentioned before, in previous studies concerning water stress, scientists compared water availability and water demand at a yearly temporal resolution. These assessments have been done to identify areas of water scarcity currently but also in the future to analyze the effects of the climate change and they have been carried out both on global and regional scales. The assessments on a regional scale focus on regions which are prone to water scarcity due to climate as well as lack of infrastructure which allows to store and transfer water resources and such an example of a region is Africa.

1.2.2. Macro-scale Hydrological Models (MHM-s)

Macro-scale Hydrological Models have been applied over the past years for the assessment of water availability, water demand and water stress (Vörösmarty et al., 2000;Oki et al., 2001; Nijssen et al., 2001b). These Macro-scale Hydrological models have some common characteristics such as a spatial and a temporal resolution of the output of some specific duration, a climatic input, and some of them share some main features. The purpose of MHMs is to model the dynamics of land surface hydrology of continental scale river basins and calculate runoff and river discharge. At the beginning of the development of such MHMs a spatial resolution of 1°, 2° or even larger was used due to input data constraints but as shown later by Yates (1997) the larger spatial resolution of 2° and 5° proved to be inadequate for producing reasonable runoff estimates across the domains of both Western Europe and Africa and this urged the development of MHM-s with finer spatial resolution.

Vörösmarty et al. (1989, 1998, 2000) developed the Water Balance (WBM) MHM with 0.5° spatial resolution (approximately 50 by 50 km grid) and a monthly temporal resolution. The climatic input of this model is from 1961 till 1990 and the output gives results concerning river discharge. Alcamo et al. (1997, 2000, 2003a) came up with Water-Global Assessment and Prognosis (WaterGAP 1.0/2.0) which uses the same spatial resolution like the Water Balance (WBM) MHM (0.5°) but with a daily temporal resolution. The duration in this case is from 1950 till 2025 for the water use (Agriculture, Industry and Domestic) and 1961-1990 for runoff and ground water recharge.

Besides these MHMs mentioned above there are several others which similarly calculate river discharge, runoff, groundwater discharge but some calculate all of them or a combination of them. All these models use a common spatial resolution (0.5°) but the temporal resolution varies from days to 10-days till months. Some other examples of

MHM's is the Bucket Model developed by Takahashi et al. (2000), Total Runoff Integrating Pathways (TRIP) by Oki et al. (2001) and finally Water and Snow Balance Modeling System (WASMOD-M) proposed by Widén-Nilsson et al. (2007). Wada et al. (2011) makes use of PCR-GLOBWB (PCRaster GLOBal Water Balance) which was developed by the Department of Physical Geography, Utrecht University (Van Beek et al., 2011).

1.3. Scientific Question and Research Objective

The main research question, this study will try to answer is how the seasonal variation of water stress is characterized on a global scale for the year 2000 and what is the portion of the total population affected by high degrees of water stress. This assessment will try to describe the water stress conditions globally in the year 2000 on a monthly temporal resolution and also in terms of net water demand. This is the first time that a water stress assessment study focuses on the net water demand of all the three sectors (Industry, Agriculture and Households) and tries to quantify net water demand for each sector separately.

According to Wada et al. (2011) both irrigation water demand and domestic water demand are characterized by a large seasonal variability depending on the growing season of the different types of crops and the variation of the temperature over the year, respectively. Regarding industrial water demand there is a little information concerning its seasonal variability; however Van Vliet et al. (2012) claim that river discharge and water temperature influence the potential for industrial cooling water use, therefore during periods with high water temperatures and low stream flow risks may arise for the thermoelectric power production due to cooling water shortages. In this study we will try to describe water stress throughout the year simply by implementing a finer temporal resolution. Governmental organizations as well as institutions dealing with water supply issues are interested in water stress assessments which will allow them to know when and where a potential water scarcity event will occur in order to take precautionary measures to limit it.

According to Vassolo and Döll (2005) global-scale information on industrial water demand only exists as 'total industrial water demand per country' and it does not provide for spatial distribution within the countries, which is necessary to assess the water situation in river basins. Additionally, there has not been a lot of work done in the past concerning the industrial water demand, thus the calculation of industrial water demand for the year

2000 is the main objective of this study and this will be achieved by implementing the most recent methods and by using the latest available data sets. Due to data constraints this study will estimate water demand for all the three sectors (Industry, Agriculture and Households) for the year 2000 as bench mark year and contrast it against 43 years (from 1958 until 2000) of long term climate variability.

1.4. Methodology and Approach

With the reassessment of the industrial net water demand being the primary objective of this study, the methodology followed in this assessment is described briefly in this section. The year 2000 was chosen as benchmark year because simply it is the only year for which the availability of data is not as limited as it is for other years. The methodology we follow is identical to the methodology proposed by Vassolo and Döll (2005). In their assessment the global industrial water withdrawals and water use were estimated for the year 1995 as benchmark year and we implemented the same approach in GIS (Geographic Information System) environment, to estimate the industrial net water demand for the year 2000. Their methodology introduces for the first time the distinction between the fraction of water that is used for cooling thermal power stations and the fraction of water that is supplied to manufacturing firms and treats each one in a different way (for more detailed information see chapter 2).

For the water stress assessment the WSI (Water Scarcity Index) is used but instead of using water withdrawals (or gross water demand) we take into account the sum of the net water demand of all the three sectors (industrial, agricultural and domestic). The domestic water demand is calculated by implementing the temperature function of Wada et al. (2011a). The irrigation water demand, as well as the blue water availability (e.g. river discharge) for each month of the year 2000, was provided by Wada et al. (2011b). Finally, the desalinated water use and the groundwater abstraction is calculated following the methodologies of Wada et al. (2011b) as they are described in the following chapters of this assessment.

1.5. Data Requirements

1.5.1. Water Withdrawal and Socio-economic Data

We complemented the water demand data of Wada et al. (2011, 2012) regarding water withdrawal, reservoir characteristics and population with an assessment of industrial water demand similar to that of Vassolo and Döll (2005). For the latter we require information on the exact location (coordinates) of the Power Plants of the world (fossil fuel and nuclear), as well as, their energy production for the year 2000. Besides that, we also need data providing us with information about the cooling system type of each Power plant. All these data mentioned above can be found on the website of CARMA (CARbon Monitoring for Action; http://carma.org/dig/show/energy+plant#top) and from the National Geospatial- Intelligence Agency (NGA; http://earth-info.nga.mil/gns/html/cntry_files.html). For the reassessment of industrial water demand we also need data for the production volumes of all the countries for the eight different sectors we include in this assessment (beer, cement, chemicals, crude steel, paper and paperboard, pig iron and sugar; Vassolo and Döll, 2005) for the year 2000 which can be obtained from United Nations (UN; http://data.un.org/Explorer.aspx?d=ICS) and Central Intelligence Agency (CIA; https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html). Data concerning desalinated water use and groundwater abstraction based on country statistics can be obtained from Earth Trends (WRI: World Resources Institute; http://earthtrends.wri.org/) and AQUASTAT (FAO: Food and Agriculture Organization of the United Nations; http://www.fao.org/nr/water/aquastat/data/), as well as from the International Groundwater Resources Assessment Centre (http://www.un-igrac.org/publications/331). Additionally socio-economic data such as GDP (Gross Domestic Product) per capita, which will be used for the classification of the countries into emerging, developing and developed for our analysis, are obtained from the World Bank (http://www.worldbank.org/). All data sources and detailed descriptions are given in chapters 2 and 3.

1.5.2. Validation

In a study based on available datasets it is important to evaluate the input (meteorological datasets) and validate the output (e.g. runoff, water withdrawal) in order to remove any errors prior to the application of the model and to check the performance of the model, respectively. In the past, scientists in relevant studies evaluated the meteorological input (= potential weakness) simply by using different data sources and validated the output by comparing their results with observation data or with results of other studies. Such an example of study is that of Hanasaki et al. (2007a); they used different forcing data sources like the GSWP, the ISLSCP, the CRU and the ERA-40 to evaluate the input and validated the output (runoff) by comparing their results with the observation data from GRDC (Global Runoff Data Centre) and the results of other studies (Döll et al., 2003; Nijssen et al., 2001b). Similarly, Wisser et al. (2008) used different meteorological datasets and maps of irrigated area to explore uncertainties.

For the validation of the output of this study we will use the results of other studies to compare them with. The components we are going to validate are industrial water withdrawals, as it will be estimated, with annual published country specific industrial water withdrawals for year 2000 and finally the population that experienced high degrees of water stress in the same year with the findings of other similar studies. In this study we are interested in industrial water demand and not in industrial water withdrawals but due to the fact that there has not been done a lot of work in the past, concerning industrial water demand, we are going to validate industrial water withdrawals for the year 2000. According to the methodology we follow in this study industrial water demand will be derived from water withdrawals, thus we can compare the calculated industrial water withdrawals for the year 2000 with published values of industrial water withdrawals (AQUASTAT/FAO; www.fao.org/nr/water/aquastat/data/query/results.html).

2. Complementary Data

2.1. Water Availability at a Monthly Time Scale

The water availability data as well as the irrigation water demand were provided to us by Wada et al. (2011a). In order to compute continental runoff they used PCR-GLOBWB forced with the meteorological data sets of both the ERA-40 (duration: 1957-2002) and the CRU (duration: 1958-2001). The first generated values of continental runoff much higher than other previous studies (table 2.1), something that could cause overestimation in water availability (i.e. the total river discharge). Therefore, Wada et al. (2011b) used the simulated runoff based on the meteorological data of the CRU to estimate water availability. River discharge was calculated by accumulating all specific runoff along the LDD (Local Drain Direction), but first by taking into account possible positive gain due to rainfall or negative due to evaporation over open surface. Then, this storage was routed along the LDD using the kinematic wave approximation of the Saint-Venant Equations (Chow et al., 1988) and the river discharge was calculated as shown in figure 2.1. A numerical solution of the kinematic wave approximation is available as an internal function in PCR-GLOBWB.

In the past years scientists tried to describe the effect of reservoir operation on river discharge by building reservoir operation schemes (e.g. Vörösmarty et al., 1997; Meigh et al., 1999; Nilsson et al., 2005; Haddeland et al., 2006; Hanasaki et al., 2006; Van Beek et al. 2011). Van Beek et al. (2011) coupled a reservoir operation scheme with PCR-GLOBWB similar in nature to the scheme developed by Haddeland et al. (2006) with the difference that this scheme is prospective in contrast to the existing schemes of Haddeland et al. (2006) and Hanasaki et al. (2006) that involve a retrospective regulation on the basis of the simulated discharge and demand. This means that despite the fact that such a retrospective regulation would ensure optimum reservoir performance given its purpose and the given values of inflow and demand, a prospective scheme has to work with uncertain forecasts of future inputs and demands, a reality that confronts reservoir operators on a daily basis. Wada et al. (2011a) used the prospective reservoir scheme developed by Van Beek et al. (2011) in order to calculate the river discharge under the influence of reservoirs operation. After they simulated river discharge with the operation of reservoirs they compared their results with observation data and they concluded that although the reservoir operation scheme does not fully represent actual reservoir operations, it reasonably reproduces actual monthly fluctuations and it is useful to couple with global water balance models to simulate river discharge, which improves accuracy of temporal trends. Figure 2.2 shows the differences between the mean river discharge (m^3 $month^{-1}$) with reservoir operation and without reservoir operation, in the four seasons over the years 1958 and 2000.

Table 2.1: Continental runoff based on data and model based estimates in km$^{3}\cdot$year^{-1} (Wada et al., 2011b)

Continents		**Europe**	**Asia**	**Africa**	**North America**	**South America**	**Oceania**	**Global (except Antarctica)**	**Time Period**
Data based estimates									
Baumgartner and Reichel (1975)		2564	12,467	3409	5840	11,039	2394	37,713	-
Korzun et al. (1978)		2970	14,100	4600	8180	12,200	2510	44,560	-
L'vovich (1979)		3110	13,190	4225	5960	10,380	1965	38,830	-
Shiklomanov (1997)		2900	13,508	4040	7770	12,030	2400	42,648	1921-1990
GRDC (2004)		3083	13,848	3690	6294	11,897	1722	40,533	1961-1990
		2925	*13,423*	*3993*	*6809*	*11,509*	*2198*	*40,857*	-
Model based estimates									
Fekete et al. (2000)		2772	13,091	4517	5892	11,715	1320	39,319	-
Vörösmarty et al. (2000)		2770	13,700	4520	5890	11,700	714	39,294	1961-1990
Nijssen et al. (2001b)		-	-	3615	6223	10,180	1712	36,006	1980-1993
Oki et al. (2001)		2191	9385	3616	3824	8789	1680	29,485	1987-1988
Döll et al. (2003)		2763	11,234	3592	5540	11,382	2239	36,687	1961-1990
Widén-Nilsson et al. (2007)		3669	13,611	3738	7009	9448	1129	38,605	1961-1990
		2833	*12,204*	*3933*	*5730*	*10,536*	*1466*	*36,566*	-
PCR-GLOBWB (ERA-40)		**2810**	**20,965**	**12,794**	**8343**	**16,749**	**4963**	**66,623**	**1961-1990**
PCR-GLOBWB (ERA-40)		**2724**	**18,864**	**6223**	**7256**	**15,010**	**6112**	**56,187**	**1957-2002**
PCR-GLOBWB (CRU)		**2472**	**12,513**	**8118**	**4651**	**13,992**	**2765**	**44,511**	**1961-1990**
PCR-GLOBWB (CRU)		**2476**	**11,365**	**7208**	**4508**	**13,487**	**2701**	**41,745**	**1958-2000**

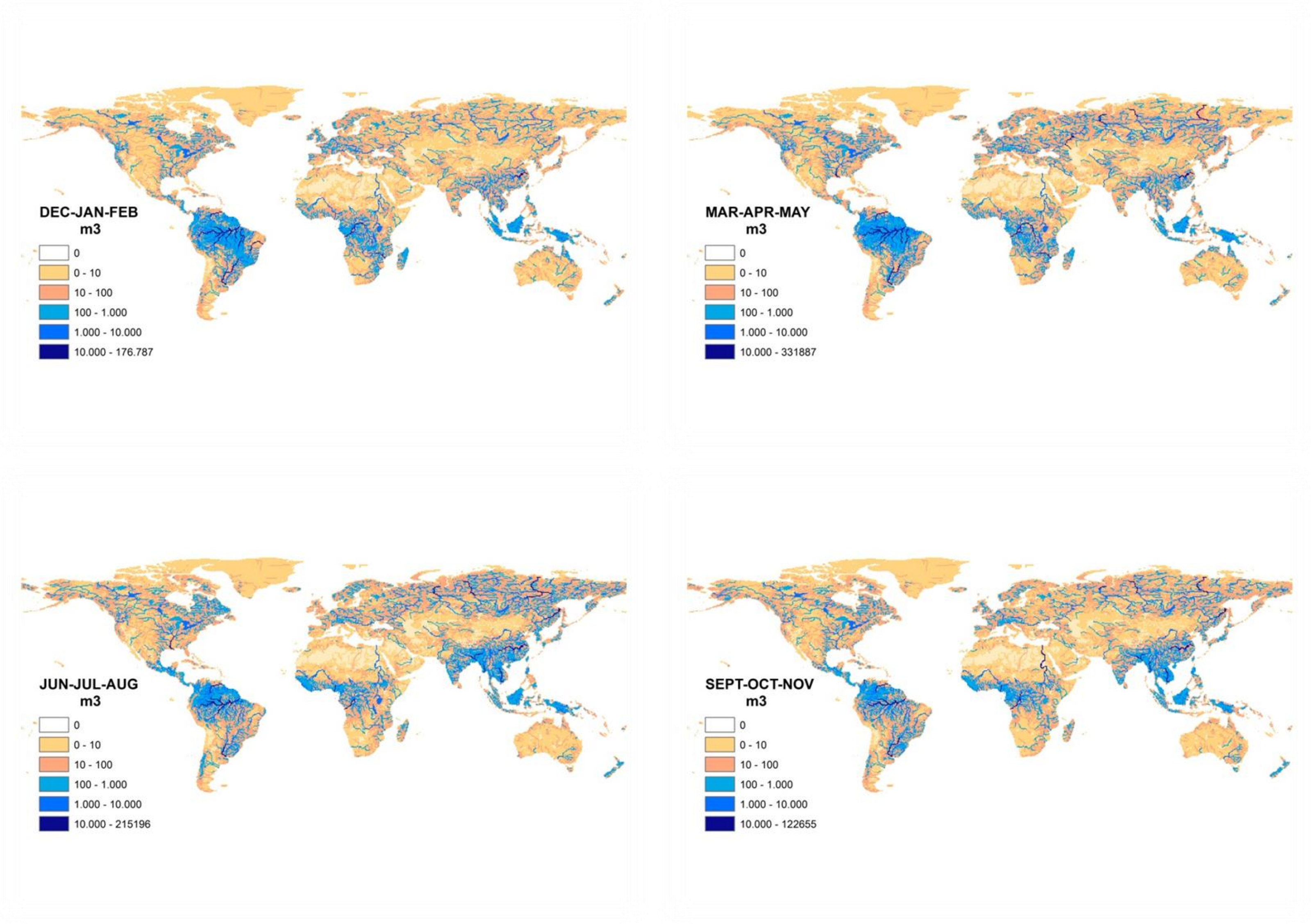

Figure 2.1 Mean river discharge (m^3 $month^{-1}$) in the four seasons over the years 1958 and 2000

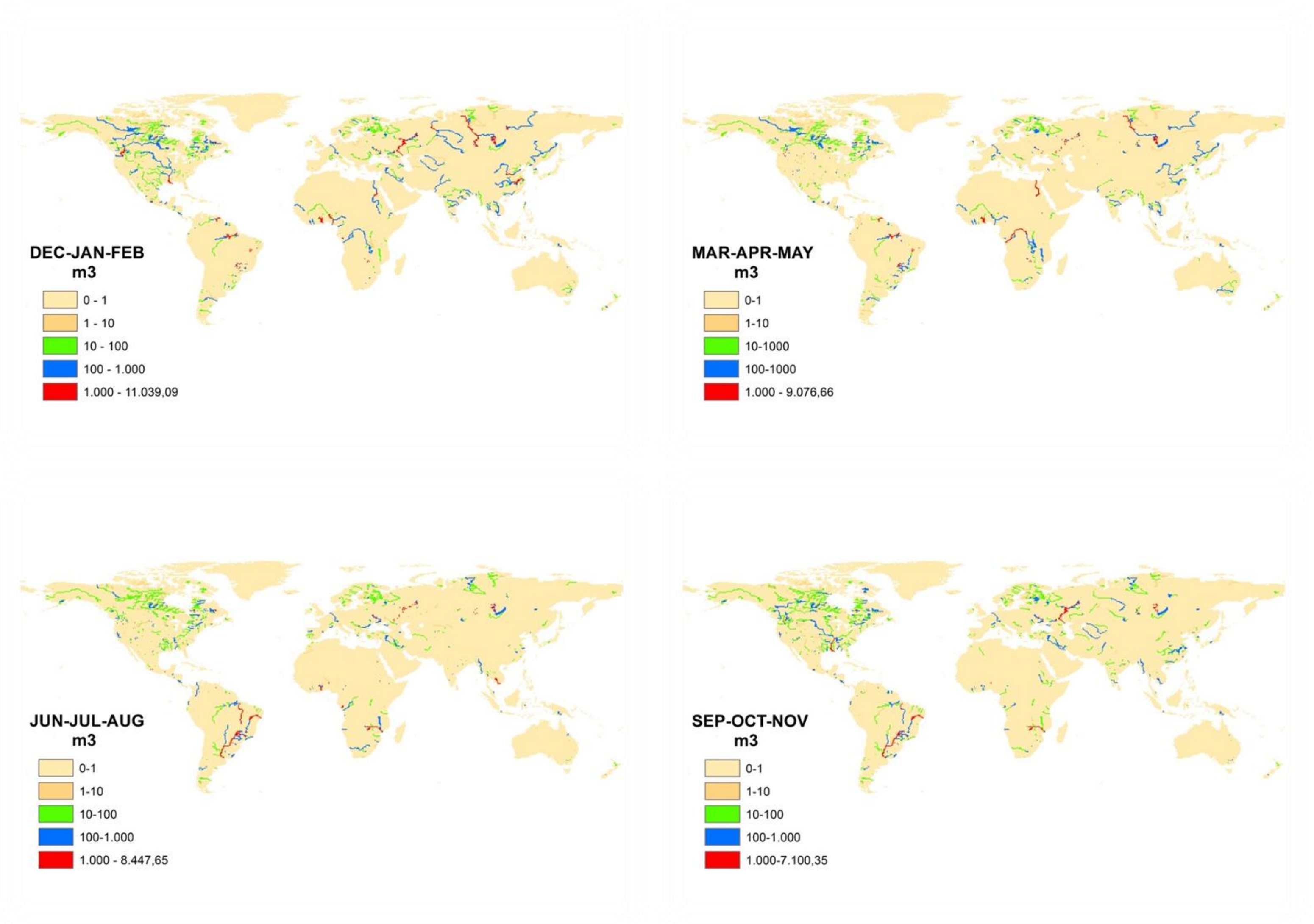

Figure 2.2 Differences between the mean river discharge (m^3 month^{-1}) with reservoir operation and without reservoir operation, in the four seasons over the years 1958 and 2000

2.2. Irrigation Water Demand

As mentioned above, the irrigation water demand data were provided to us by Wada et al (2011a). They used the latest available dataset of monthly areas and crop calendars for 26 crops around the year 2000 (MIRCA2000). Wada et al (2011a) calculated irrigation blue water demand for each 0.5° cell by using the simulated potential and actual evapotranspiration from PCR-GLOBWB. Crop specific potential evapotranspiration for the irrigated areas was calculated from the effective crop factor at 0.5° for the 26 irrigated crop types (MIRCA2000) and the reference potential evapotranspiration. For more information we refer to Wada et al. (2011a). Figure 2.3 shows the average net irrigation water demand in the four seasons over the years between 1958 and 2000.

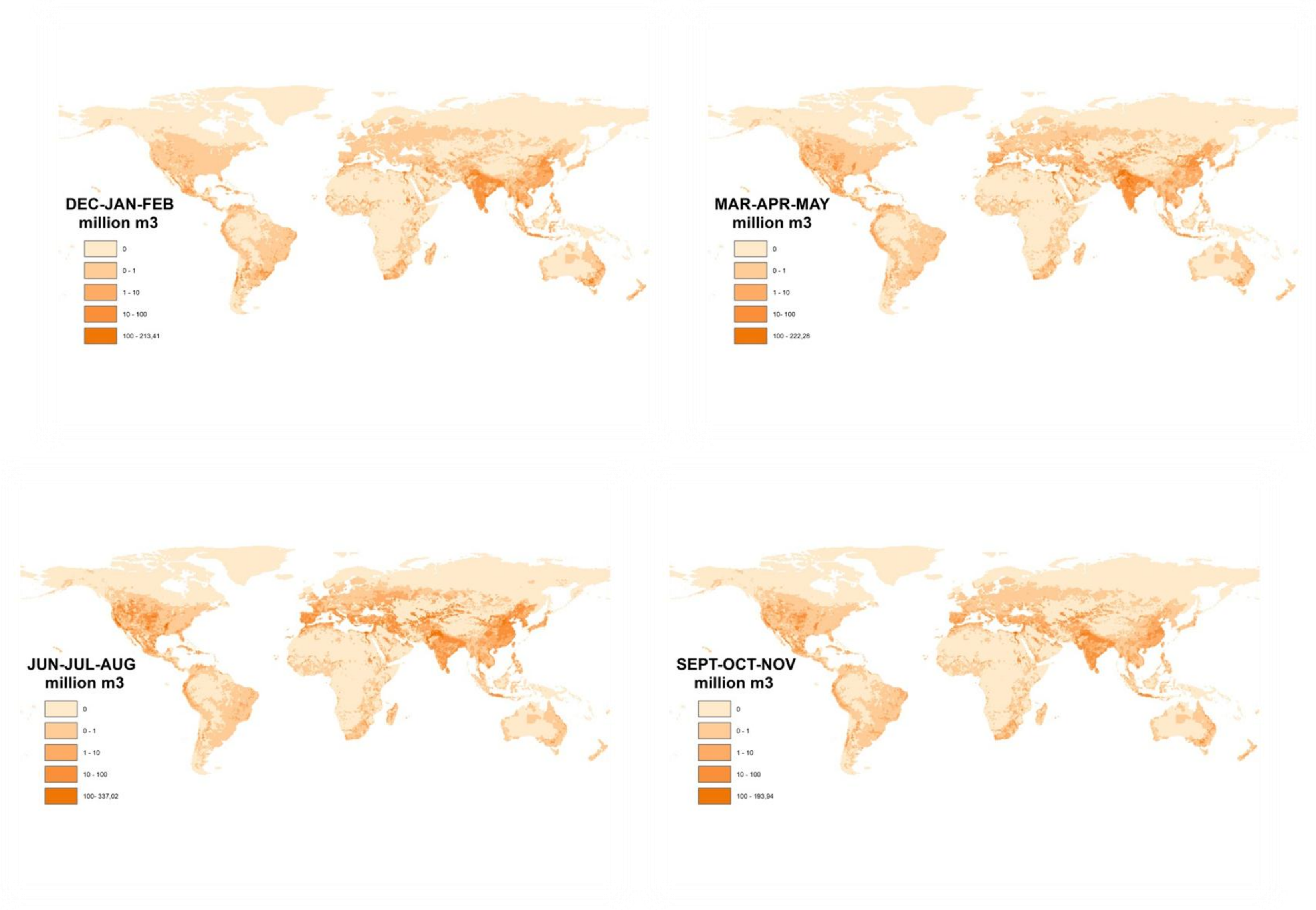

Figure 2.3: Average net irrigation water demand (million $m^{3}\cdot month^{-1}$) in the four seasons over the years between 1958 and 2000

3. Water Demand and Water Stress Assessment at a Monthly Time Scale

3.1. Introduction

Global water demand is partitioned over three sectors comprising agriculture (livestock and irrigation), industry (thermal power stations and manufacturing firms) and households. Usually water demand refers to the demand for blue water availability, unless it is described differently. This study is interested in blue water demand and green water was not included in the assessment. Besides the water demand for blue water we will also include water use from particular resources such as desalinated water and groundwater. Desalinated water use and groundwater abstraction are part of total water demand, with the difference that its source is the sea water and groundwater respectively and the amount of desalinated water and groundwater abstraction is added to the available freshwater resources.

Globally water demand has increased for most countries over the past decades, as a result of constant demographic and economic growth. Table 3.1 shows the statistics of population and water use by sectors (%) based on continents and GDP per capita classes in the year 2000 (FAO AQUASTAT; Gleick et al., 2006; Wada et al., 2011a and World Bank). Agricultural water use is by far the largest among the three sectors which represents about the 68.6 % (most of it is for irrigation whereas livestock takes up only a small amount) of the total water use, second comes Industrial water use with 18.1 % and last is Domestic (households and municipalities) water use with 13.3 % (FAO AQUASTAT, Gleick et al. 2006).

Looking at the water use on a continental scale we can see clearly that the situation is different from the global case. In Europe and North America industrial water use is the largest among the three sectors with 48.5% and 33.9% respectively whereas in Africa, Asia and South America the agricultural water use is about 85%, higher than the global average. This suggests a correlation between water use and economic development and table 3.1 validates this argument. Low income countries have an increased water use for agriculture, whereas high income countries show high water use for industry and middle income countries correspond more to the global average.

In this study industrial, domestic and livestock monthly water demand were computed by in a GIS environment and for the irrigation water demand were used the results of Wada et al. (2011). Gridded data for the year 2000 on water withdrawal available from the WWDR-II (World Water Development Report II) were used. In addition, country statistics data from Earth Trends (WRI) and AQUASTAT (FAO) and gridded data of global livestock density from FAO (2007) were obtained. For the industrial water demand we obtained the data from several sources. For the water demand of the thermal power production we used the available data sets from CARMA (CARbon Monitoring for Action) and from the National Geospatial- Intelligence Agency (NGA) in order to disaggregate the country specific water demand for the supply of the manufacturing firms to grid cells with 0.5° spatial resolution. The procedure we follow for the industrial sector is similar to this of Vassolo and Döll (2005) with the difference that they calculate water withdrawals and water consumption but in our case we calculate initially water withdrawals and from this we derive industrial net water demand as it is described later in this chapter.

Studies regarding water demand (Wada et al., 2011a; Hanasaki et al., 2008a, 2008b and Hoekstra et al., 2012) in the past few years have increased the temporal resolution and as a result the resolution of water stress assessments has been increased. For the agricultural water demand, as mentioned before, there has been a lot of work done to quantify it on both yearly and monthly temporal resolution but for the industrial water demand most studies focus on a yearly temporal resolution. Hence the biggest challenge of this study is to re-estimate industrial water demand on a monthly scale. According to the methodology we are following in this study in order to estimate the industrial water demand on an increased temporal resolution (e.g. month) we are going to need monthly data concerning the electricity production of each of the power plants globally as well as the monthly production of each of the eight manufacturing sectors for the year 2000. Such data are not available, with a few exceptions (e.g. United States of America), thus the industrial water demand is assumed to be constant over the year.

Table 3.1: Population in the year 2000 and 2010 and water use by sectors (%) based on continents and GDP per capita classes in the year 2000

	Population in 2000 (millions)	**Population in 2010 (millions)**	**Total Freshwater Withdrawal (km^3·year^{-1})**	**Per Capita Withdrawal (m^3·capita^{-1}·year^{-1})**	**Agricultural Use (%)**	**Industrial Use (%)**	**Domestic Use (%)**
Continents							
Africa	818.7	1031.22	213.2	260.4	**83.1**	**4.3**	**12.6**
Asia	3679.8	4142.96	2294.8	623.6	**84.9**	**7.2**	**7.9**
Europe	729.2	721.78	392.2	537.8	**29.3**	**48.5**	**22.2**
North America	476.1	541.03	622.5	1307.5	**44.1**	**33.9**	**22.0**
South America	341.2	392.99	164.6	482.4	**84.8**	**6.4**	**8.8**
Oceania	28.7	34.09	26.3	916.4	**64.9**	**10.4**	**24.7**
Low Income Countries[2]	2203.2	2489.91	1288.2	584.7	**86.0**	**7.7**	**6.3**
Middle Income Countries[3]	2961.7	3347.11	1549.4	523.2	**69.0**	**16.1**	**14.9**
High Income Countries[4]	908.8	1027.06	875.7	963.6	**39.6**	**39.4**	**21.0**
Globe	6073.7	6864.08	3713.7	611.4	**68.6**	**18.1**	**13.3**

[1] These data are based on FAO AQUASTAT, Gleick et al. (2006) and Pacific Institute, The World's Water website; http://www.worldwater.org/data.html. If there is no data in the year 2000, data in the year 2001 was used.

[2] GDP per capita of low income countries is less than 755 US dollar (year 2000 US dollar; country classification by the World Bank in the year 2000/2001) and the average GDP per capita of these countries is 358.9 US dollar.

[3] GDP per capita of middle income countries is between 756-9265 US dollar (year 2000 US dollar; country classification by the World Bank in the year 2000/2001) and the average GDP per capita of these countries is 2,842.5 US dollar.

[4] GDP per capita of high income countries is more than 9266 US dollar (year 2000 US dollar; country classification by the World Bank in the year 2000/2001) and the average GDP per capita of these countries is 21,879.6 US dollar

3.2. Industrial water demand

3.2.1. Introduction

Industrial freshwater withdrawals (gross industrial water demand) account for approximately 20% of the total global withdrawals. These withdrawals vary widely from country to country, depending mainly on the country's level of economic development. High-income countries use, on average, 59% of their withdrawn water for industrial purposes whereas low-income countries only 8% (Vassolo and Döll, 2005; Oki and Kanae, 2006). The importance of knowing the global distribution of industrial water demand is not only relevant to the problem of water scarcity, but also of water quality, as the management and disposal of industrial wastewater use may lead to severe water pollution (Vassolo and Döll, 2005 and Van Vliet et al., 2012).

So far, global-scale information on industrial water withdrawal only exists as ''total industrial water withdrawals per country'' (WRI, 2000; Shiklomanov, 2000; AQUASTAT) with the only exception the dataset of WWDR-II which contains information about the industrial water use in the year 2000 with a , while estimates of industrial water consumption (amount of withdrawn water that evaporates to the atmosphere during use) are given by Shiklomanov (2000) as a ratio of the withdrawal for 26 world regions. Unfortunately, these data sets do not provide for spatial distribution within the countries, which is necessary to assess the water situation in river basins. Vörösmarty et al. 2000 and Alcamo et al. 2003 distributed the country values of industrial water withdrawals to 0.5° grid cells based on urban population. Up to this point, in all existing global data sets of industrial water use and water withdrawals there was no distinction between the fraction of water used for cooling thermal power stations and the fraction supplied to manufacturing. In 2005 Vassolo and Döll were the first who made such a distinction and presented global scale 0.5° gridded estimates of industrial water withdrawal and consumptive water use for the year 1995. These estimates help to better assess the global water situation, especially the current water use situation in river basins, because they allow the distinction of two very dissimilar industrial water uses that differ with respect to their consumption-to-withdrawal ratio.

In this study we will follow the methodology proposed by Vassolo and Döll (2005) to estimate the industrial water withdrawals both for the cooling of thermal power stations and the manufacturing firms. For the estimation of the water withdrawals (gross water demand) for the cooling of thermal power stations we need various data such as specific locations of the thermal power stations globally (fossil fuel, nuclear, geothermal), energy production of each thermal power station for the year 2000, as well as, information about the cooling system type of each thermal power station. For the water withdrawals (gross water demand) for the supply of manufacturing firms we will need data concerning the production volumes for each manufacturing sector, as well as, the sector specific water intensity.

3.2.2. Water use (Net Water Demand) for the Cooling of Thermal Power Stations

For the estimation of the water withdrawals of the thermal power stations globally the dataset available by CARMA (CARbon Monitoring for Action; http://carma.org/dig/show/energy+plant) was used. This data set contains information for the specific location of each of the 53,979 thermal power stations globally which were processed in GIS environment and were distributed as shown in figure 3.1 (fossil fuel, nuclear and geothermal) as well as the amount of energy produced by each of the thermal power stations in the year 2000. The procedure followed in this study is similar to the one by Vassolo and Döll (2005). The annual water withdrawal of each of 53,979 thermal power stations is estimated first and the water withdrawals of all stations within the grid cell are then added. The total amount of water withdrawn by all *n* power stations in a cell was computed as follows:

$$TWW = \sum_{i=1}^{n} EP_i * WI_i(Cs_i)\,, \tag{3.1}$$

where EPi is annual electricity produced by a thermal power station i within the cell (MWh/yr), WIi is station-specific water withdrawal intensity (m^3/MWh), which depends on the cooling system of the station Cs_i, and n is the number of stations in the cell.

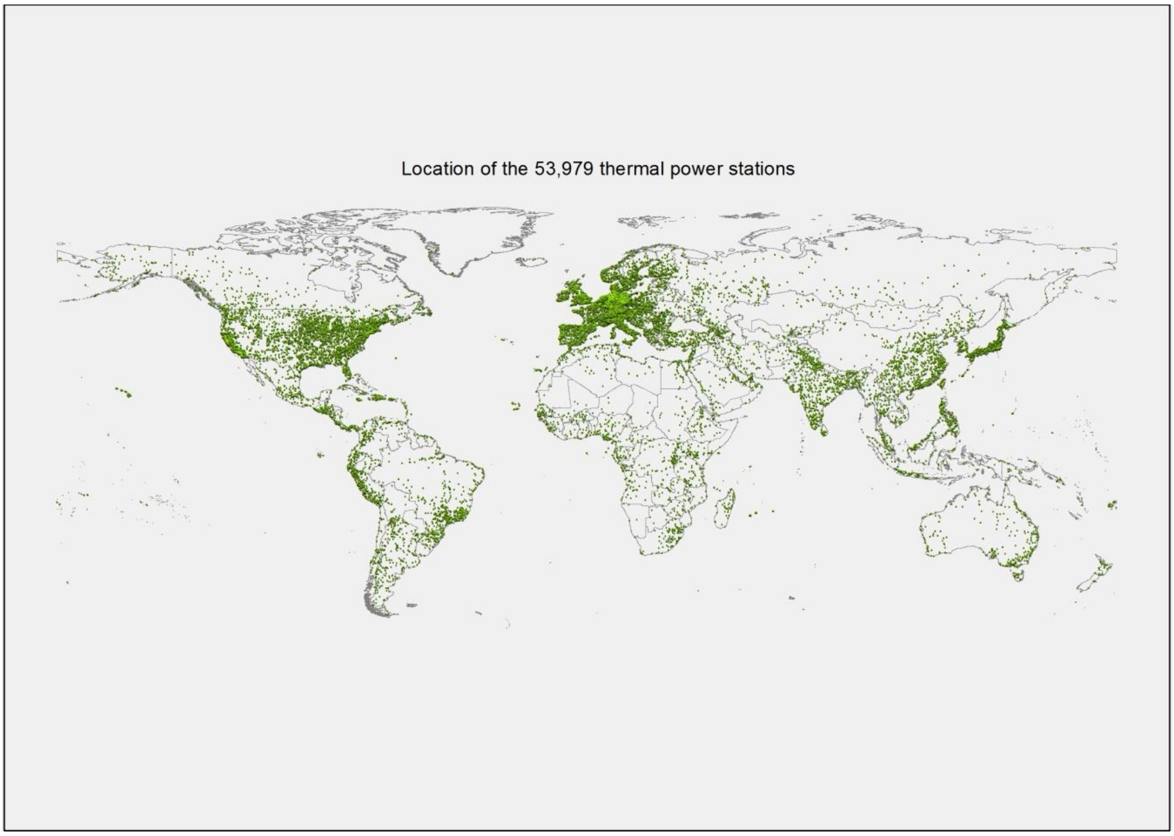

Figure 3.1: Location of the 53,979 thermal power stations.

According to Vassolo and Döll (2005) the amount of water withdrawn or consumed by a power station is driven solely by the type of cooling system installed. Mainly two types can be distinguished: the ‘‘one through flow’’ system and the ‘‘cooling tower’’ system. In the first case, cooling water is returned to the source immediately after it has cooled down the condenser. This system requires very high water withdrawals per unit of produced electricity, but the consumption is a very small fraction of the withdrawal (0.36%). In the ‘‘cooling tower’’ system, the cooling water flows in a closed circuit. The heat is removed from the cooling water by contact with the air in the cooling tower. The withdrawal in this system is low, as water leaves the station mainly by evaporation in the tower (consumption) and not by return flow to the source and the water consumption per unit of produced electricity is approximately twice as high as for the ‘‘one-through flow’’ cooling system but still less than the water withdrawal. Since not all of the withdrawn water is used, but only a small portion of it, in both cooling system types and the rest is returned to the system as return flow we can describe net water demand in terms of water consumption and gross water demand in terms of water withdrawal. Because no information concerning the cooling system type of each of the thermal power station is available we assumed that, due to the fact that ‘‘one-through flow’’ cooling requires large volumes of water and its discharge heats up the river, ‘‘cooling tower’’ systems would prevail in 0.5^o cells with low river discharge and high electricity production to prevent excessive warming. Therefore, ‘‘one through flow’’ cooling systems are mainly installed in cells where electricity production is below 100 GWh/(cell year) and discharge is larger than 0.3 km^3/year. For all the other cells we assumed that the ‘‘cooling tower’’ system has been installed. Vassolo and Döll (2005) did the same in their study with the difference that for the discharge they used the WaterGAP model.

To define the water consumption intensities for each cooling system (‘‘one through flow’’ and the ‘‘cooling tower’’) we used the values proposed by Vassolo and Döll (2005). They used data from various power station operators or related authorities and statistically analyzed them. The values they obtained are 0.65 m^3/MWh for thermal power stations with ‘‘one-through flow’’ cooling and 1.33 m^3/MWh for thermal power stations with ‘‘cooling tower’’. Figure 3.2 shows the thermoelectric water consumption (net water demand) in 2000. The largest withdrawals occur in highly industrialized regions like the eastern United States and Western Europe, but also in the western part of Eastern Europe and in China. In all other regions, thermoelectric water withdrawals are only important in certain industrialized centers.

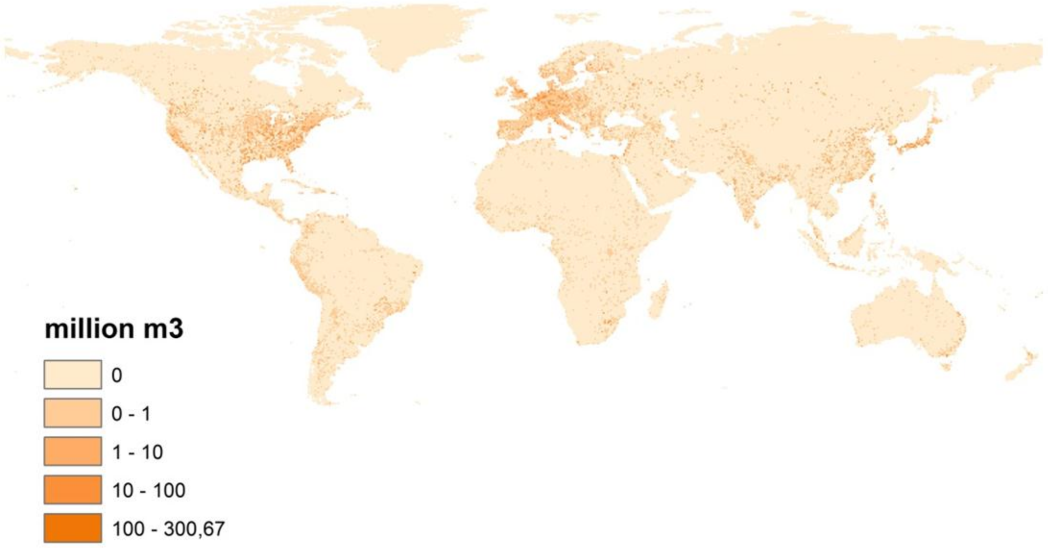

Figure 3.2 Net monthly water demand for the cooling of thermal power stations for the year 2000

3.2.3. Water Withdrawals (Gross Water Demand) for the Water Supply of Manufacturing Firms

Withdrawn freshwater resources are not used entirely, but some part of them is returned to the system depending on the recycling ratio of each county. According to the methodology we follow in this assessment in order to quantify the net water demand for the supply of manufacturing firms, initially we have to estimate the gross water demand (water withdrawals) and from that we will estimate the net water demand. Therefore water withdrawals (gross water demand) play an important role in this assessment. For the estimation of the water withdrawals for the supply of manufacturing firms we followed the method proposed by Vassolo and Döll (2005). In our assessment we included the same eight (8) manufacturing sectors, chemicals, paper, pig iron, fabrics, crude steel, sugar, beer, and cement. Among these manufacturing sectors chemicals, paper, pig iron, fabrics, crude steel and sugar are those with the highest water intensities for the production of one ton of product in m^3/ton (see table 3.2), whereas the other two (beer and sugar) were used to obtain manufacturing water use in poor countries where other manufacturing activity is nonexistent. Country-specific total manufacturing water withdrawal (MWW, in m^3/year) was calculated as follows:

$$MWW = \sum_{i=1}^{8} VP_i * WI_i \,, \tag{3.2}$$

where *VPi* is the annual production volume of each of the eight manufacturing sectors (ton/year), and *WIi* is the sector-specific water intensity (m3/ton).

The production volumes of the eight manufacturing sectors of each country for the year 2000 were obtained from the United Nations data center (http://data.un.org/Explo-rer.aspx?d=UNESCO) and for those countries we did not find any records on the United Nations data center, they were obtained from the Central Intelligence Agency World Factbook (https://www.cia.gov/library/publications/the-world-factbook/inde-x.html). The sector-specific water intensities as shown in table 3.2 were obtained from the literature (Vassolo and Döll, 2005). The availability of the sector specific water intensities is limited with some exceptions of some developed countries (High Income countries in the year 2000/2001 according to the World Bank) such as the United States of America, Canada, Germany and United Kingdom. For the rest countries, we simply categorized them into Low Income (developing), Middle Income (emerging) and High Income (developed) based on the country classification by the World Bank in the year2000/2001. Then we took the average of the water intensities of the high income countries, we found records for, and assigned this average values to the other ‘high income’ countries. For the ‘low income’ countries we assigned the value of the country with the highest specific water intensity and for the ‘middle income’ countries the value of the country with the second highest specific water intensity and we did this for each manufacturing sector. By doing so, we took into account the recycling ratio of each country and therefore the development stage of each country which will allow us to increase the detail of our assessment. Vassolo and Döll (2005) in their assessment took the average of the water intensities of the countries, they found records for, and assigned this average value to the remaining countries without taking into account the development stage of each country like we did.

After annual country values of the water withdrawals for the supply of manufacturing firms were estimated they were distributed onto 0.5^{o} grid cells proportional of the city lights at night time. To do this we followed the method of Oda et al. (2006) by using the city lights at night time data set for the year 2000 available by the National Oceanic and Atmospheric Administration (NOAA NGDC; http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html). Oda et al. (2006) also calculated the correlations between the radiance lights and the population for 20 countries and they concluded that among the 20 countries the overall population and the nightlights are well correlated, which practically means that this method of spatial disaggregation sufficiently distinguishes urban from rural population. The data set mentioned above is available with a resolution of 30 arc seconds (approximately 1km by 1km) which we had to transform it into a resolution of 0.5^{o} grid cells. The distribution was formed by superimposing the nightlight data and country boundary data, which were used to identify the country attributes of pixels. Radiance light quantities across all cells attributed to a country were summed, and the original quantity at each pixel was normalized by the country sum. The water withdrawals for the supply of manufacturing firms intensity at a pixel was obtained by multiplying the normalized radiance with the annual total country water withdrawals for the supply of manufacturing firms.

Figure 3.3 shows the water withdrawals for the supply of manufacturing firms, which are based on distributing country values proportional to the city lights at tight time. In the case of manufacturing, the highest withdrawals take place in Europe and eastern Asia where the industrial activity is high. To validate the methodology for estimating the total water withdrawals, the computed values are compared with data from the literature for selected countries as shown in table 3.3. All literature values are for 2000 with some exceptions which are around 2000 (1999-2002) and were found on the website of Food and Agriculture Organization of the United Nations. (http://www.fao.org/nr/water/aquastat/data/query/results.html). The values calculated for India, France, China and United States of America show significant deviation with the published values whereas the values calculated for the rest countries of table 3.3 are consistent with the published values. For all the other countries which are not included in the table 3.3 the values agree well.

Table 3.2: Sector-specific water intensities (m^3/ton)

Country	Beer m^3/t	Cement m^3/t	Chemicals m^3/t	Crude Steel m^3/t	Paper m^3/t	Pig Iron m^3/t	Sugar m^3/t	Fabrics m^3/t
Canada	9,3[2]	8,5[2]	345[1]	-	157[1]	190[1]	-	-
USA	9[2]	7,6[2]	600[5]	6[2]	180[3]	86[2]	9[2]	200[4]
China	-	-	-	56[2]	-	-	-	-
Japan	-	-	-	56[2]	-	-	-	-
Austria	10[5]	-	-	15[5]	150[5]	-	15[5]	-
Belgium	9,3[2]	-	-	-	-	-	-	-
Denmark	3,4[5]	5,4[5]	-	-	-	-	10[2]	-
Finland	9[2]	-	-	-	100[2]	-	10[2]	110[2]
France	25[5]	-	-	63[2]	150[2]	-	21[5]	110[2]
Germany	-	-	1200[6]	-	50[6]	96[6]	10[2]	-
Ireland	8[5]	-	-	-	-	-	-	-
Israel	13,5[5]	11,9[2]	-	-	-	-	2[7]	-
Norway	10[5]	-	-	30[5]	20[5]	-	-	-
Russia	-	-	-	63[2]	223[2]	-	-	-
South Africa	-	-	-	-	-	-	-	350[8]
Spain	6[5]	-	-	30[5]	250[5]	-	3,5[5]	8[5]
Sweden	4[5]	5,2[5]	-	5,3[5]	20[5]	-	0,5[5]	45[5]
UK	6,5[5]	-	-	100[5]	20[5]	-	1,5[5]	110[5]
Average (Rest of Developed)	**9,5**	**7,7**	**715**	**39**	**120**	**124**	**8,3**	**133**
Developing	25	11.9	1200	100	250	190	21	350
Emerging	13.5	8.5	600	63	223	96	15	200

[1] Major Withdrawal Uses of Water from Canada Statistics Web site (http://www.statcan.ca/english/Pgdb/envir05.htm, accessed 2001), [2] Carmichael and Strzepek [1987], [3] ITT Industries, Guidebook to Global Water Issues (available at http://www.itt.com/waterbook/ind_USA.asp), [4] U.S. Environmental Protection Agency Web site (http://www.epa.gov), [5] European Environmental Agency [1999], [6] Statistisches Bundesamt [1998], [7] Rogers [1998], [8] Lumby [1999].

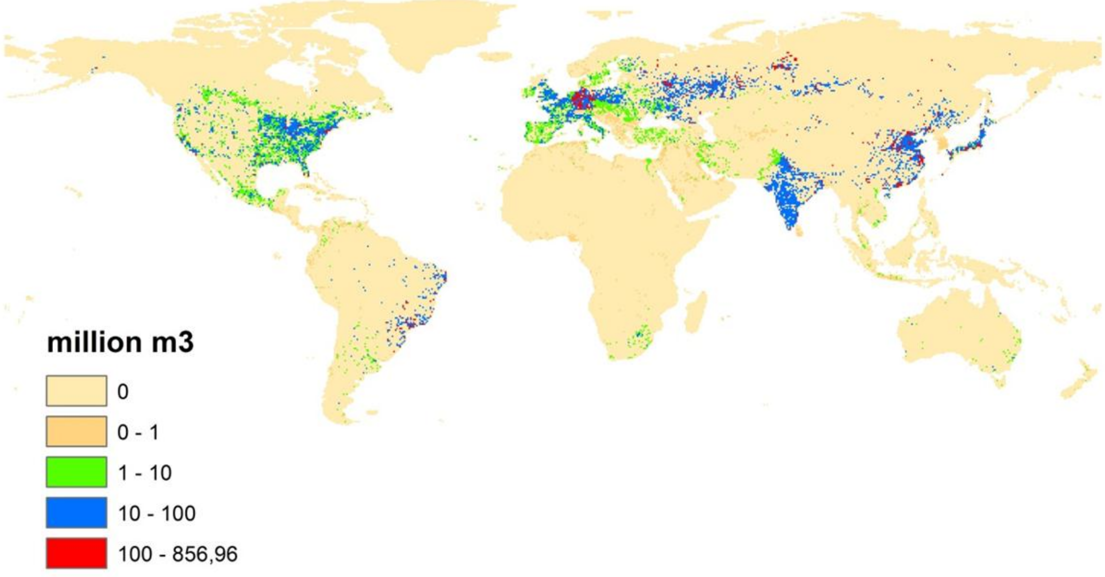

Figure 3.3 Water withdrawals for the supply of manufacturing firms for the year 2000

Table 3.3: Comparison between estimated and reported (AQUASTAT-FAO) water withdrawals for the cooling of thermal power stations and the supply of manufacturing firms.

Country	Estimated millions m^3	Reported millions m^3	Performance ratio [%]
United States	223000	213000	4.69
China	118000	127700	7.59
Russia	37800	39600	4.54
Germany	33000	32600	1.22
Canada	31800	31570	0.72
France	24100	21970	9.69
Italy	15750	16290	3.31
Japan	16300	15800	3.16
Ukraine	14100	13990	0,78
Brazil	11000	10650	3.28
India	11850	10000	18.5

[1] Values for 2000 from AQUASTAT/FAO (http://www.fao.org/nr/water/aquastat/data/query/results.html)

3.2.4. Water Use of Manufacturing Firms (Net Water Demand)

As mentioned in previous parts of this study, economic growth and industrial development have a direct impact on the water resources of the countries. At present there are many regions of the world where water demand exceeds availability and as the population keeps growing this problem becomes more severe. Consequently, the need of water recycling in industry is of high priority. Oki et al. (2001) suggest that the recycling ratio in industry is 86% of the total withdrawals. Oki and Kanae (2006) found that the recycling ratio in the industry of Japan which is a developed country is nearly 80%. This means that approximately the 80% of the total withdrawn water is reused in industry, in developed countries, whereas in the developing China about 60-65% was recycled in 2004 (MWR, 2007). This indicates that the more developed a country is the more water is recycled in industry.

Estimates of previous studies (Alcamo et al., 2003b; Oki et al., 2001; Shiklomanov, 2000; Vörösmarty et al., 2000) overestimate industrial water demand on a global scale due to the fact that the recycling ratio was not taken into account. Thus it is important to consider the recycling ratio in industry in order to take as plausible estimates as possible. The problem is that that the availability of data regarding recycling in industry is limited, therefore we will follow the method of Wada et al. (2011a) to estimate the recycling ratio by interpolating the recycling ratio for other countries based on the historical data of the recycling ratio of Japan.

The data we used for the interpolation is the recycling ratios in industry between 1965 and 2007 from the Ministry of Land, Infrastructure and Transport (MLIT; http://www.mlit.go.jp/) in Japan and from the World Bank (http://data.worldbank.o-rg/indicator/NY.GDP.PCAP.CD). From 1965 to 2007 Japan went through three development stages (developing, emerging and developed) according to the dataset of GDP per capita so we classified Japan into developing (low income from 1965 to 1969), emerging (middle income from 1970-1979) and developed (high income 1971-2007) and for these three stages of development we took the average of recycling ratio which we assigned to the rest countries of the world based on their classification in 2000 as shown in table 3.4. After doing so, we estimated the net water demand of the manufacturing firms simply by multiplying the interpolated recycling ratio of each country with the total water withdrawals. Figures 3.5 and 3.6 show the monthly net water demand for the supply of manufacturing firms and the total monthly net industrial water demand respectively. After we estimated the annual and the monthly industrial water demand as well as the annual and monthly total net water demand we found the ratios of the monthly industrial net water demand to the monthly total net water demand and the annual industrial net water demand to the annual total net water demand as shown in figures 3.7 and 3.8. By doing so we highlighted the areas globally where the industrial sector is dominant among the three sectors. The areas where the ratio is close to one show that at these specific locations the industrial water demand is equal to the total water demand, whereas when it is close to zero it means that the industrial water demand is close to zero too and the water demand is dominated by the rest of the sectors. We can see clearly that developed regions mostly are dominated by industrial water demand such as North Europe and Eastern United States of America.

Table 3.4: Interpolated recycling ratio of developing, emerging and developed countries

Time period	Development stages of Japan	GDP per capita (in US dollars in 2000)	Mean Ratio
1965-1969	Developing (Low income)	≦755	42.1%
1970-1979	Emerging (Middle income)	756-9265	64.3%
1980-2007	Developed (High income)	≧9266	76.6%
1965-2007	Total		69.3%

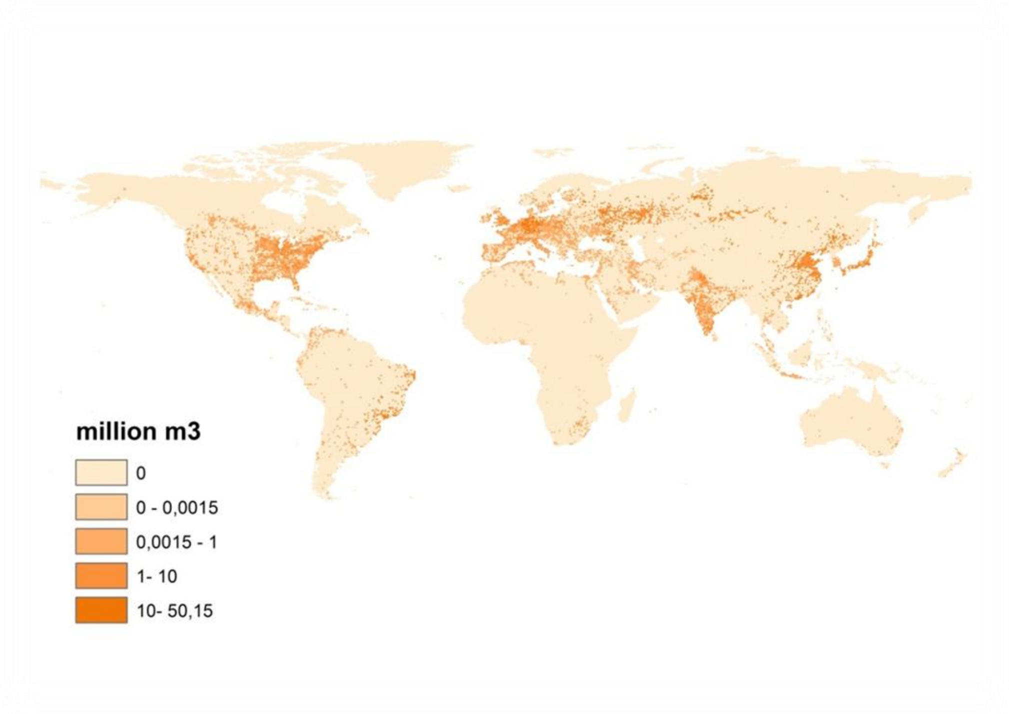

Figure 3.5 Net Monthly water demand for the supply of manufacturing firms for the year 2000

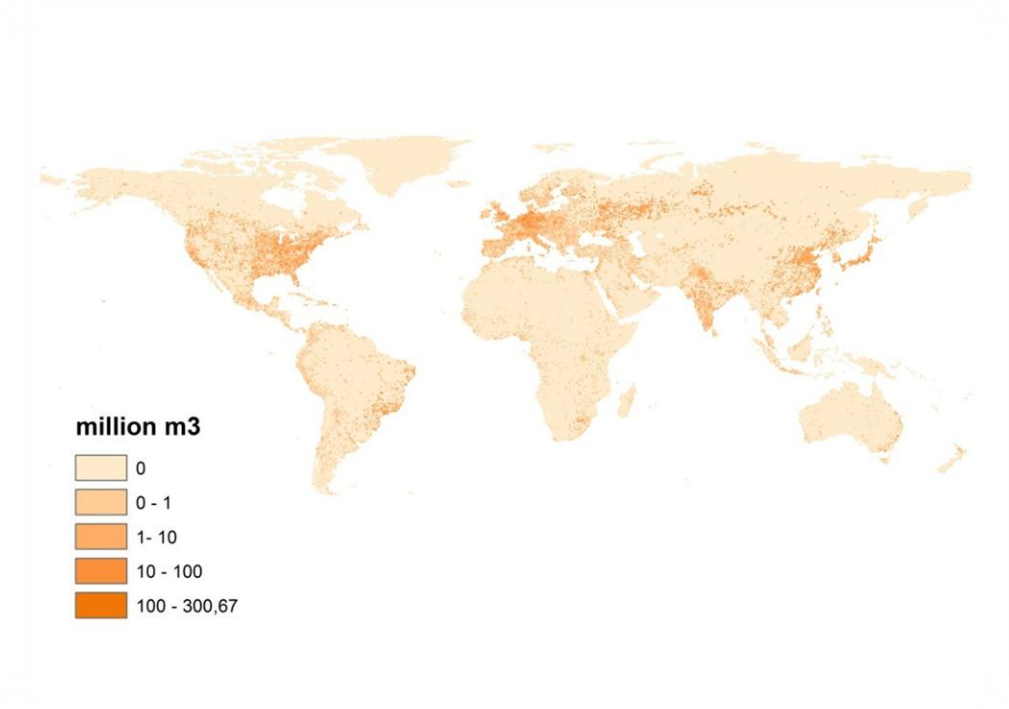

Figure 3.6 Total net monthly industrial water demand for the year 2000

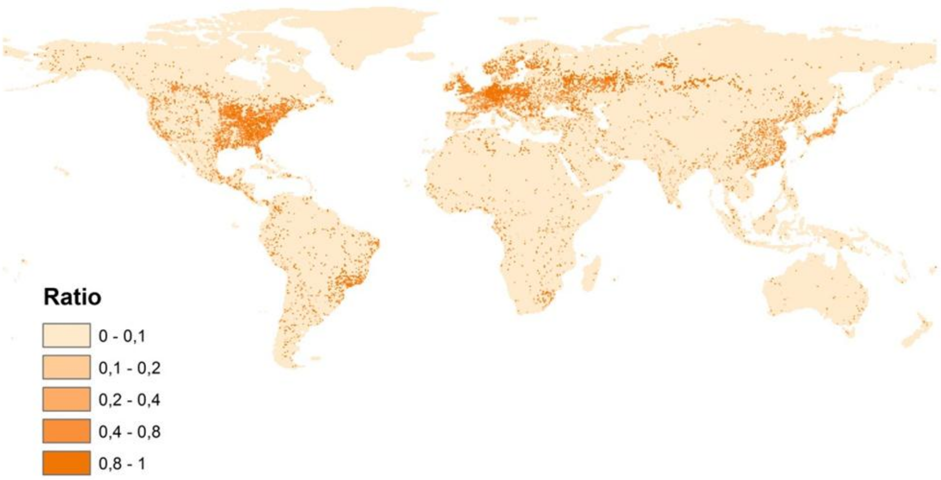

Figure 3.6 Ratio of the annual industrial net water demand to the annual total net water demand

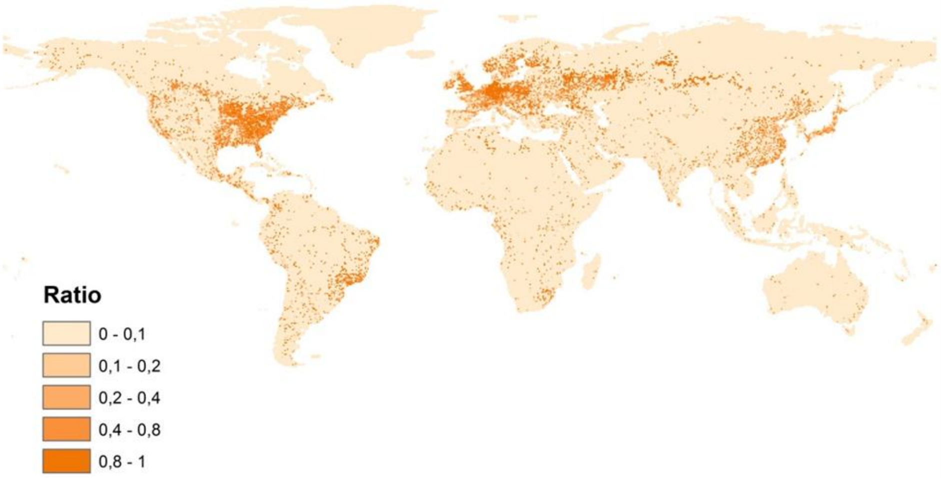

Figure 3.7 Ratio of the monthly industrial net water demand to the monthly total net water demand

3.3. Livestock Water Demand

Total agricultural water demand is divided into three subcategories, irrigation water demand, livestock water demand and water demand of rainfed agriculture. In this study we are interested in the first two subdivisions of the total agricultural water demand, irrigation and livestock water demand and not in the third because water demand of rainfed agriculture is part of green water availability and in this study we are only interested in blue water availability. Compared to the total water use, livestock water use occupies a very small portion of it (about 1-2% of the total water use) but in areas where irrigation water use is low it plays an important role as stated by Flörke and Alcamo (2004).

For the estimation of the livestock water demand we followed the methodology proposed by Alcamo et al. (2003a) which later on, was implemented also by Wada et al. (2011a). This method estimates annual livestock water demand at a spatial resolution of 0.5° and takes into account the grid-based distribution of six major types of livestock (Cattle, Buffaloes, Goats, Sheep, Pigs, Poultry/Chicken) and the water consumption rate of each one of them. The data concerning the spatial distribution of livestock were obtained from Food and Agriculture Organization of United nations (FAO, Global livestock densities for the year 2000, http://www.fao.org/ag/AGAinfo/resources/en/glw/GLW_dens.html) and from Alcamo et al. (1997) for the water consumption per day for each of the six types of livestock. This data set from Food and Agriculture Organization of United nations, regarding the spatial distribution of livestock, is provided at a spatial resolution of 0.05° (3 minutes or 5km by 5km at the equator) and in order to process it we had to change it at a spatial resolution of 0.5° and then we simply multiplied the number of livestock of each grid cell with the corresponding daily water consumption, given by Alcamo et al. (1997) as shown in table 3.5.

After the estimation of annual livestock water demand for the year 2000 we disaggregated the annual values to monthly values (figure 3.8). To do so it was necessary to assume that livestock water demand is constant throughout the year, which means that the value of each grid cell remains constant from January to December as shown in figure 3.8.

Table 3.5: Daily water consumption rate of six major types of livestock (Alcamo et al., 1997).

Livestock	***Water consumption rate (m3/day)***
Buffaloes	*0.025*
Cattle	*0.025*
Goats	*0.00225*
Pigs	*0.004*
Poultry/Chickens	*0.000028*
Sheep	*0.00225*

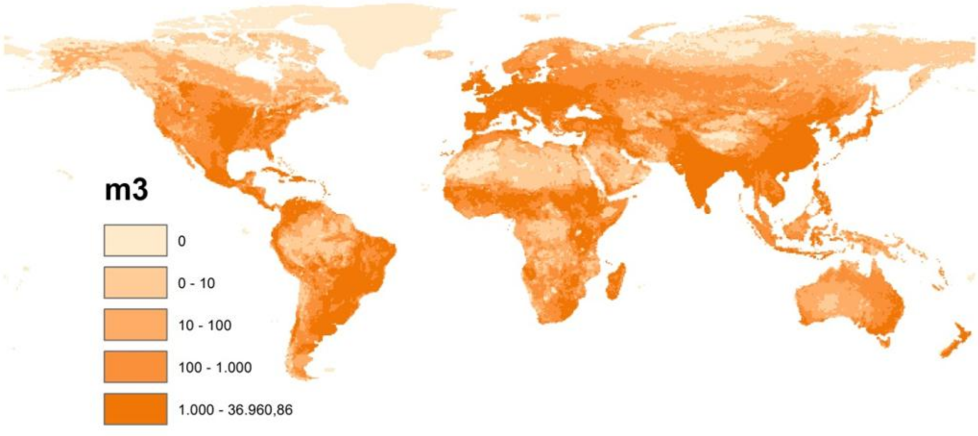

Figure 3.8 Monthly livestock water demand for the year 2000.

3.4. Domestic water demand

Domestic water demand mainly is distributed for the water use of households and municipalities. As mentioned before in other sections of this study, domestic water demand occupies the 13.3% of the total water use globally and it is driven by the population growth and the economic development (Kundzewicz et al., 2007), similarly to industrial water demand. In general people in developed countries consume about 10 times more water daily than those in developing countries. According to Shiklomanov (2000) a large amount of withdrawn water for the supply of households and municipalities is returned to the river networks as waste water and this amount of returned water depends on the development of the cities, thus on the development of the countries.

For the estimation of the monthly domestic water demand we implemented formula 3.4, developed by Wada et al. (2011a). We initially assumed monthly domestic water demand as constant over the year by disaggregating the yearly data. According to formula 3.4 various data are needed for the estimation of the domestic water demand. Water withdrawal data were obtained from WWDR-II (http://wwdrii.sr.unh.edu/download.html) and the climatology data from CRU climatology. Wada et al. (2011a) used formula (3.3) to estimate the amount of water that is actually used but the results did not show any significant values related with return flow on the reuse of domestic water demand. Therefore, we will use the same recycling ratio as we used in industry.

$$D_{dom,return} = D_{dom,month} * (1 - (U_{fraction} * R_{recycling,ind})) , \tag{3.3}$$

where $D_{dom,return}$ is the amount of water that is actually used considering return flow to river networks (million m^3•$month^{-1}$), $D_{dom,month}$ is monthly domestic water withdrawal (million m^3•$month^{-1}$), $U_{fraction}$ is the fraction of urban population over total population (-) and $R_{recycling\ ,ind}$ is the recycling ratio developed for water recycling in industry (-).

In general, there is a high demand around summer for households and municipalities (June to September in the Northern Hemisphere and December to March in the Southern Hemisphere). Therefore, the assumption that domestic water demand is a function of temperature, as it is shown in figure 3.9, is necessary, although it is influenced by various other variables. The formula developed by Wada et al. (2011a) for the estimation of the domestic water demand is described as follows:

$$D_{dom,month} = \frac{D_{dom,annual}}{12} \cdot \left(\left(\frac{T - \overline{T_{avg}}}{T_{\max} - T_{\min}} \cdot R_{dom,month} \right) + 1 \right), \tag{3.4}$$

where $D_{dom,month}$ is monthly domestic water demand (million $m^3 \cdot month^{-1}$) and $D_{dom,annual}$ is annual domestic water demand based on the WWDR-II (million $m^3 \cdot year^{-1}$). T, T_{avg}, T_{max} and T_{min} are temperature, average temperature, maximum temperature and minimum temperature, all monthly average, respectively (°C), based on CRU climatology (duration: 1961-1990).

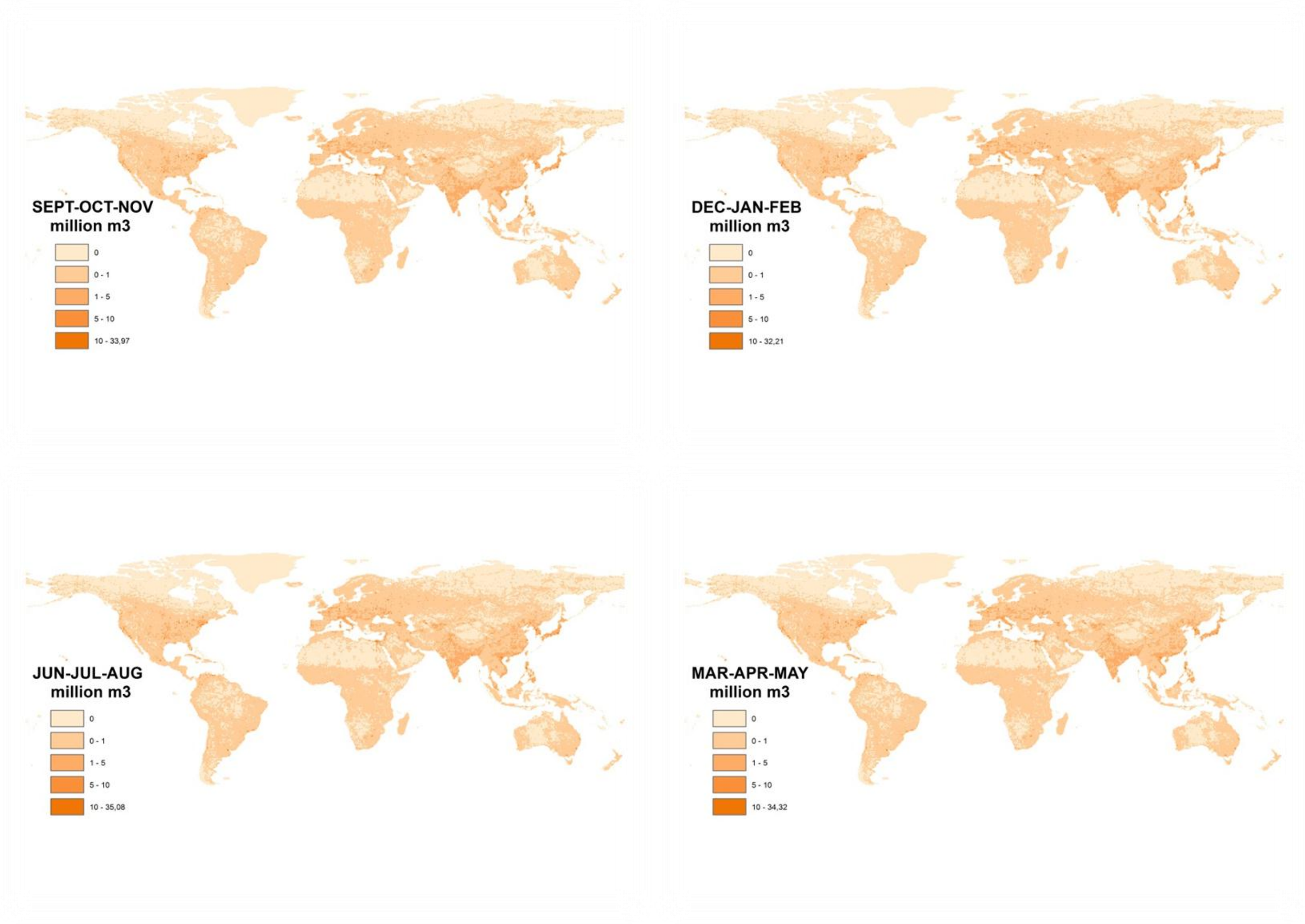

Figure 3.9 Average domestic water demand (million m$^{3}\cdot$month^{-1}) in the four seasons for the year 2000

3.5. Desalinated Water Use

In countries and regions where available freshwater resources are limited, desalinated water use is an alternative source of water. Despite the fact that there is a high concern regarding the environmental impacts of the high energy consumption according to Kundzewicz et al. (2007) for the production of desalinated water, the amount of the yearly production is increasing with the years. In the year 2000 the countries with the highest desalinated water use was Kazakhstan and Saudi Arabia as shown in table 3.6. The amount of water that is desalinates is mostly used to cover the needs of the industrial and domestic (households and municipalities) sectors.

For the estimation of desalinated water use we followed the methodology proposed by Wada et al. (2011a). The availability of desalinated water use data is high (Earth Trends, AQUASTAT-FAO) and it is on a country level but the quality of most of them is low. The most complete and reliable data set is available by AQUASTAT FAO (http://www.fao.org/nr/water/aquastat/data/query/results.html). For this assessment we used this dataset provided by AQUASTAT FAO which contains the most records among all the available datasets and for the countries that there were no records for the year 2000 we used the records of the years 1999 and 2001. Population gridded data available from the Socioeconomic Data and Applications Center (http://sedac.ciesin.columbia.edu/gpw/global.jsp) were used to downscale the country statistics to 0.5° grid cells while taking sub-grid variability of country borders into account. We calculated population density up to 40 km from the coast. Due to lack of monthly desalinated water use data we assumed that desalinated water use is constant throughout the year. In figure 3.10 is shown the monthly desalinated water use (in million $m^3 \cdot month^{-1}$).

Table 3.6 Countries with the highest desalinated water use in 2000.

Country	**Desalinated water use (million m^3)**
Kazakhstan	1328
Saudi Arabia	863
United States	580
Kuwait	420,2
United Arab Emirates	385

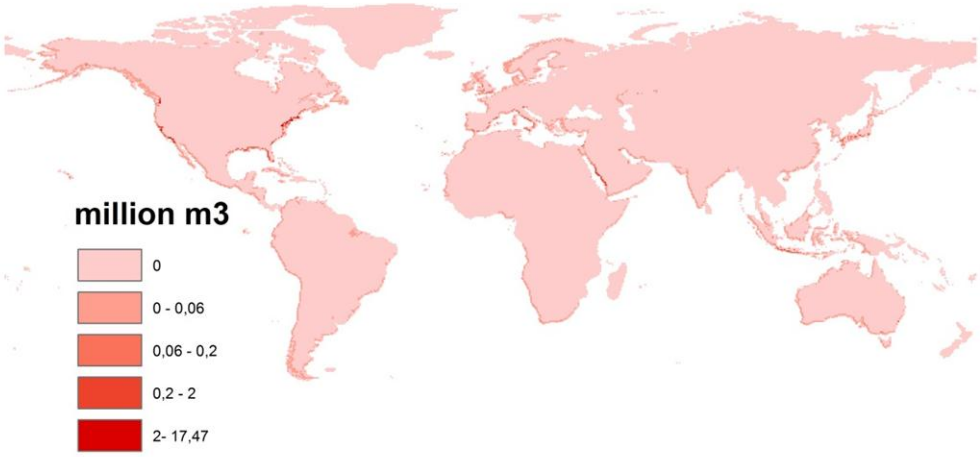

Figure 3.10 Monthly desalinated water use (million $m^3 \cdot month^{-1}$) for the year 2000

3.6. Groundwater Abstraction

In regions where surface water availability is limited both in terms of quantity and quality an additional very important source of water can be groundwater. It is generally of superior quality compared to surface water and it requires less treatment (Thyssen and EEA, 1999). On global scale groundwater resources satisfy 50% of the demand of drinking water supply, 40% of the need of self-supplied industry and 20% of the irrigation water demand Wada et al. (2011a). The demand for groundwater resources is likely to increase in the future due to the fact that water use globally is increasing constantly (Kundzewicz et al., 2007).

For the estimation of global groundwater abstraction we followed the method of Wada et al. (2011a). We used the latest available data set of the annual groundwater abstraction in m^3 per capita per country and this of the major groundwater regions of the world. We obtained these data sets from the Global Groundwater Resources System (GGRS) of the International Groundwater Resources Assessment Centre (IGRAC; http://ggmn.e-id.nl/ggmn/GlobalOverview.html). Initially groundwater abstraction was indexed for the year

2000 based on the population of each country in that year. Annual groundwater abstraction was then spatially disaggregated from country specific into 0.5° by using an intensity of the annual total water demand per cell over a country. Finally groundwater abstraction was downscaled from annual into monthly values based on the monthly total water demand. Figure 3.11 shows the average monthly groundwater abstraction for the year 2000.

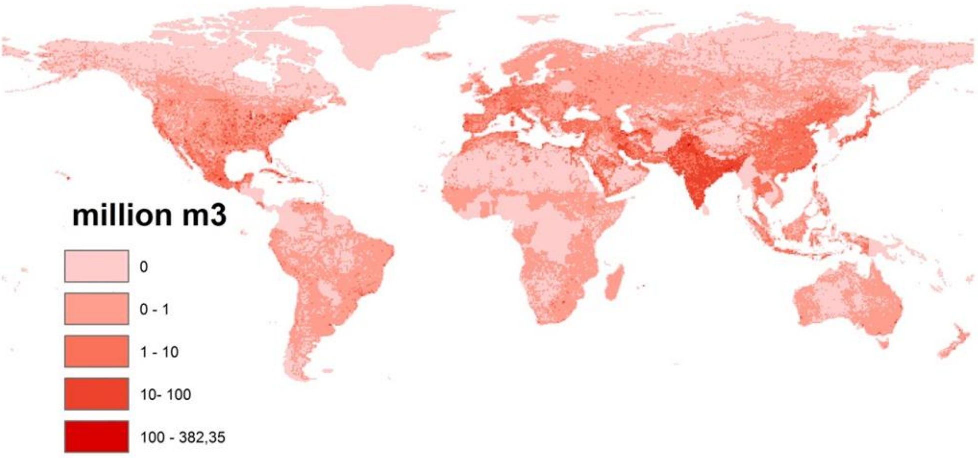

Figure 3.11 Average monthly groundwater abstraction (million $m^3 \cdot month^{-1}$) for the year 2000

3.7. Water Stress Assessment

3.7.1. Introduction

Water stress according to Flörke and Alcamo (2004) is a measure of the pressure which is applied on the water resources by the use of these sources by the agricultural, the industrial and the domestic sectors. In general, the higher the water stress is in a region the more vulnerable to water scarcity is this region. There have been several efforts in the past to investigate the countries experiencing moderate to high water stress and this carried out by United Nations (1997) estimated that about one third of the total population lives in countries which are experiencing such conditions of water stress and also projected that in the future, somewhere around 2025, about two thirds of the total population of the world could be in the same position. Other studies estimated that the number of people living under high water stress conditions is ranging from 1.2 to 2.7 billion. Examples of such studies are Alcamo et al. (2000), Arnell (1999a, 2004), Oki et al. (2001) and Vörösmarty et al. (2000).

3.7.2. Water Scarcity Index

Water Scarcity Index (WSI) is an indicator which is widely used to investigate the different degrees of water stress both on global and regional scales. In the past, besides the WSI there have been developed, as well, other indicators for the same purpose. Alcamo et al. (1997, 2000) developed the ‘criticality ratio’ which is ratio of water withdrawals over water availability, Arnell (1999a) used the use to resource ratio and Alcamo et al. (2003b) and Oki et al. (2001) used the ratio of withdrawals to water availability which is an indicator of the amount of pressure applied on the water resources by the use of these sources by the agricultural, the industrial and the domestic sectors. The ‘relative water stress index’ (RWSI) is another indicator which has been used in the past by Vörösmarty et al. (2000, 2005, 2010) for the same purpose by computing the ratio of total water demand to river discharge.

When the ratio of a specific area is high, it indicates that the available freshwater water resources within this area are used over and over again and this leads to degradation of freshwater resources of this area and this in turn implies that its use downstream of this area is limited. Usually a value of 0.4 (see table 3.7) indicates high water stress and practically it can be replaced by a per capita water availability, of 1.000 $m^3 year^{-1}$ according to Kundzewicz et al. (2007). As mentioned before a value of 0.4 could represent downstream water pollution but also the limitation to capture water but as Alcamo et al. (2000) noted, the effects of high water stress are likely to be different in different regions of the world. For instance, in developed and desert areas, an indication of high water stress shows high competition for water but not necessarily this could lead to water scarcity, whereas the same water stress indication in developing countries could be an indication of water scarcity. This triggered Alcamo et al. (2000) to carry out a sensitivity analysis concerning the threshold values of the high water stress categories by setting different values varying from 0.2 to 0.6 instead of 0.4 and their results showed that the differences between the various values (between 0.2 and 0.6) and 0.4 are insignificant. Thus in this assessment we will use the conventional Water Scarcity Index (WSI) by using a threshold value of 0.4 for high water stress.

Table 3.7 Two indicators for different degrees of water stress (Falkenmark et al., 1997; Kundzewicz et al., 2007) after Wada et al. (2011a).

Degrees of Water Stress	Per capita water availability	Water Scarcity Index (WSI) [-]	Definitions of degrees of water stress
No water stress	>1.700	WSI <0,1	No water scarcity or low
Stress	-	0,1≤ WSI <0.2	Potential water scarcity
Moderate water stress	1.700-1.000	0,2≤ WSI <0.4	Looming water scarcity
High stress	1.000-500	0,4≤ WSI <0.8	Experiencing water scarcity
Very high stress	<500	0,8≤ WSI	Economic development is limited by water scarcity

3.7.3. Monthly Water Stress Assessment

For this assessment we used monthly blue water availability of river discharge coupled with reservoir operation scheme over the period between 1958 and 2001. We also estimated monthly water demand for industry, agriculture (irrigation and livestock) and households and municipalities. The industrial and livestock water demand were constant over the year 2000 whereas the irrigation and domestic water demand were estimated for each month separately. Finally we also took into account the desalinated water use which is constant over the year 2000 and the groundwater abstraction which varies within that year. In order to assess the water scarcity on a global scale we used the Water Scarcity Index (WSI) by comparing the total water demand (industrial, irrigation and domestic) and blue water availability. In this study we estimated WSI both on an annual and a monthly temporal resolution for the year 2000.

Blue water availability:

$$W_{availability\_blue} = Q, \qquad (3.5)$$

where $W_{availability\_blue}$ is the blue water availability (million m^3 $month^{-1}$), Q is river discharge (million m^3 $month^{-1}$)

Total Water Demand:

$$W_{demand\_blue} = D_{industry} + \left(D_{irrigation} + D_{livestock}\right) + D_{domestic}, \qquad (3.6)$$

where W_{demand_blue} is the total water demand (million m^3 $month^{-1}$), $D_{agriculture}$ is the agricultural water demand (million m^3 $month^{-1}$), $D_{livestock}$ is the livestock water demand (million m^3 $month^{-1}$), $D_{irrigation}$ is the irrigation water demand (million m^3 $month^{-1}$), $D_{industry}$ is the industrial water demand (million m^3 $month^{-1}$) and $D_{domestic}$ is the domestic water demand (million m^3 $month^{-1}$).

Additional Water Resources:

$$WR_{additional} = S_{desalination} + GW_{abstraction}, \qquad (3.7)$$

where $WR_{additional}$ is the additional water resources (million m^3 month^{-1}), $S_{desalination}$ is the desalinated water use (million m^3 month^{-1}) and $GW_{abstraction}$ is groundwater abstraction (million m^3 month^{-1}).

Blue Water Stress:

$$R_{WS\_blue} = \frac{W_{demand\_blue} - WR_{additional}}{W_{availability\_blue}}, \qquad (3.8)$$

where R_{WS_blue} is the water scarcity index for blue water[-], W_{demand_blue} is the blue water demand (million m^3 month^{-1}), $WR_{additional}$ is the additional water resources (million m^3 month^{-1}) and $W_{availability\_blue}$ is the blue water availability (million m^3 month^{-1}).

Looking at the river discharge figures in chapter 2 someone can distinguish areas where water availability is equal to zero, which can cause miscalculations in the estimation of Water Scarcity Index. Formula 3.8 indicates that water availability (e.g. river discharge) is in the denominator which practically means that for these areas where water availability is zero this formula will give no results. To avoid miscalculations of this nature, for those areas, we simply examined whether there is water demand present, as well as, additional water resources. For those areas where both availability and water demand, minus the additional water resources, were zero we assigned Water Scarcity Index equal to 0 and for the areas where water availability was zero and the water demand minus the additional water resources was bigger than zero we assigned Water Scarcity Index equal to 1, which practically represents reality since in areas where availability is zero and demand is bigger than zero, there is high water stress.

4. Results and Validation

4.1. Monthly Water Scarcity Index

This study tried to estimate the Water Scarcity Index on a monthly temporal resolution on a global scale for year 2000 taking into account the long-term climate variability of 43 years (from 1958 to 2000). Figures 4.1 shows average blue water stress based on a monthly time scale (upper figure) and a yearly time scale (middle figure), for 44 years from the year 1958 to 2001 and subtraction from a monthly to a yearly time scale (bottom figure). In January the regions which suffer from high water stress (WSI>0.4) are located mostly in parts of North India, East Australia, Central Asia and Central Africa. The situation in February stays the same but regions in Southern India, West Australia and East Asia show the same behavior like the rest regions in January. March and April are months that high water stress occurs in the western parts of India, East China and Central Africa. Western parts of North America deal with high water stress in several months of year 2000 (May, June, July and August). In the summer months (June to September in the Northern Hemisphere and December to March in the Southern Hemisphere) regions located around Mediterranean Sea (Spain, Italy, Greece, Algeria and Morocco), North India, Pakistan and East China face high water stress conditions. In the rest months of the year the problem of high water stress is visible in South Africa, central parts of South America, East Europe and East Asia (regions in China and Mongolia). As described above the magnitude of water stress varies both in space and in time throughout the year due to the seasonality of both water availability (e.g. river discharge) and water demand (irrigation and domestic).

In this study we also assessed the WSI on an annual temporal resolution and the results show that there is a difference of magnitude of WSI when we are using different temporal resolutions. In our case we can identify regions where the assessment of annual and monthly water stress was mismatched (figure 4.1). For instance regions such as East Mongolia, North China, western parts of India and Pakistan, Kazakhstan, East Australia, West United States of America and finally central and southern parts of Africa show the highest differences in magnitude, which vary from 0.4 to 1 degrees.

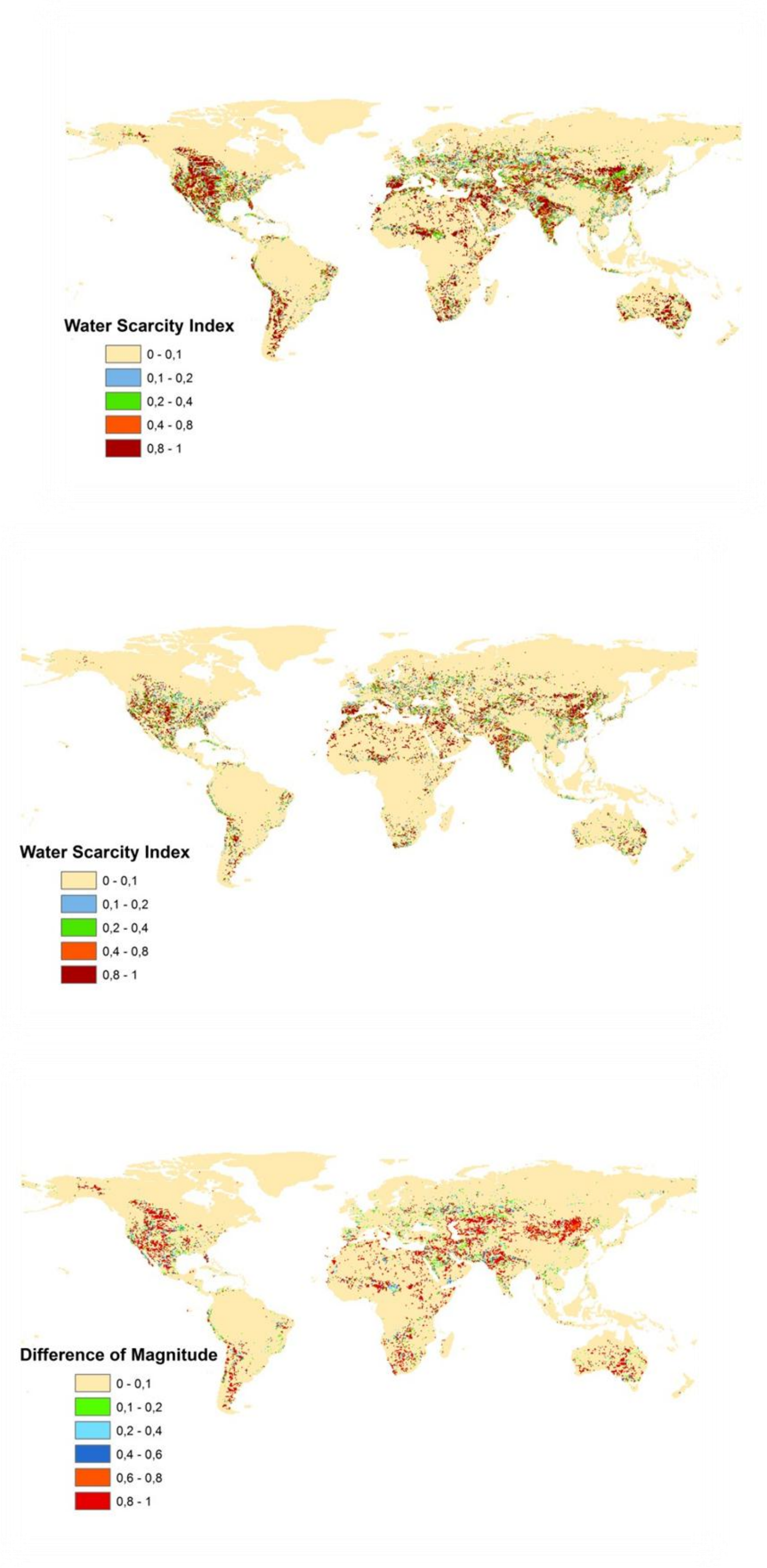

Figure 4.1: Average blue water stress based on a monthly time scale (upper) and a yearly time scale (middle) for 44 years from the year 1958 to 2001 and subtraction from a monthly to a yearly time scale (bottom).

4.2. Validation of Water Stress Assessment

In order to validate the results of this study we investigated the population of the world which experienced different degrees of water stress in the year 2000 using the Water Scarcity Index and compared our results with the results of other studies. Table 4.1 is a comparison of the results of this study with the results of other studies. Not surprisingly, this study is closer to the one carried out by Wada et al. (2011a) and the comparison shows that our results agree well with their results with a small deviation (we found about 0.21 billion less people to live under no stress conditions compared to their results), which may arise from the fact that we followed a different approach to estimate the industrial water demand, as well as, that we used the latest available datasets for the estimation of desalinated water use and groundwater abstraction. This could practically mean that past studies overestimated the amount of people living under moderate or high water stress. The population under high water stress ranges from 0.9 to 2.7 billion based on the watershed and the grid-based estimates among previous studies whereas on country based estimates varies from 0.4 to 0.8 billion. This study estimated the population under high water stress to be 1.67 billion, moderate water stress 0.6 billion, low water stress 0.62 billion and no stress 3.21 billion in a total of 6.1 billion people. The months that the most people (approximately from 1.7 billion to 1.9 billion people) experienced high degrees of water stress are January, February, March and May. The monthly variation of population under different degrees of water stress throughout the year 2000 is shown in figure 4.2.

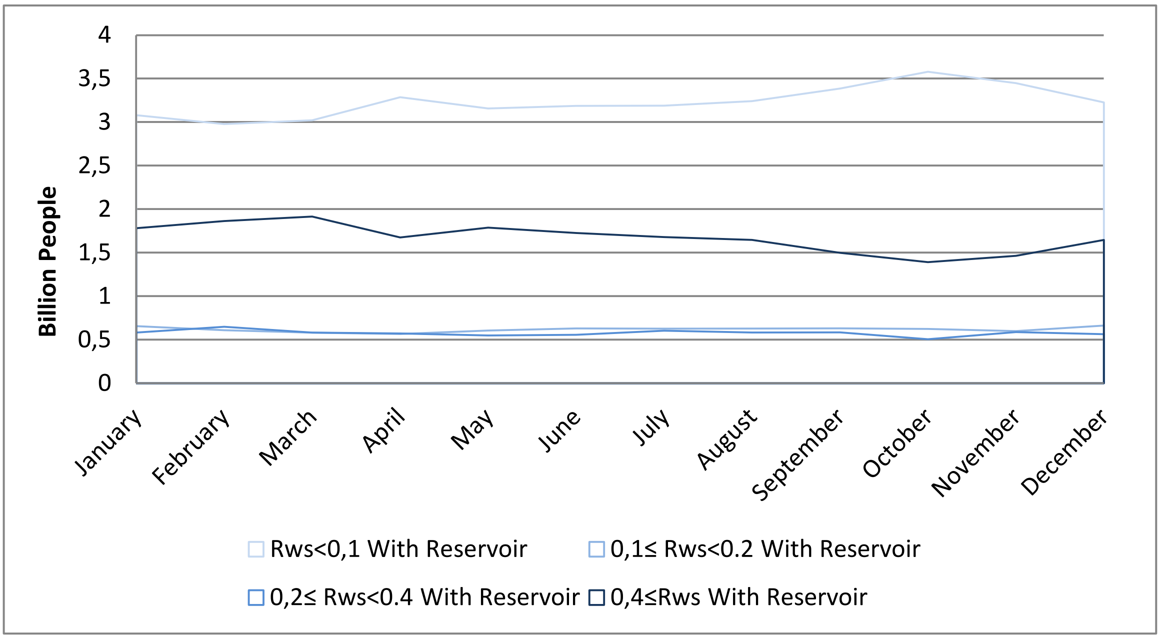

Figure 4.2 Monthly variation of population under different degrees of water stress throughout the year 2000.

Degrees of water stress	No Stress	Low Stress	Moderate Stress	High Stress	Total	Year	Spatial Resolution	Temporal resolution
Per capita water availability ($m^3 capita^{-1} year^{-1}$)	>1.700	-	1.700-100	<1000				
Rws	**Rws**<0,1	0,1≤ **Rws**<0.2	0,2≤ **Rws**<0.4	0,4≤**Rws**				
Country based estimates								
Arnell (1999a)	-	-	14	4	52	1990	Country	Year
Vörösmarty et al. (2000)	20	17	15	5	57	1995	Country	Year
Oki et al. (2001)	18	15	15	8	56	1995	Country	Year
Watershed based estimates								
Alcamo et al. (2000)	-	-	-	21	57	1995	Watershed	Year
Oki et al. (2001)	12	5	12	27	56	1995	Watershed	Year
Arnell (2004)	-	-	8	14	57	1995	Watershed	Year
Grid based estimates								
Vörösmarty et al. (2000)	32	4	4	18	58	1995	0.5^o	Year
Oki et al. (2001)	28	6	6	17	57	1995	0.5^o	Year
Arnell (2004)	-	-	8	26	57	1995	0.5^o	Year
Wada et al. (2011a)	38	6	6	11	61	2000	0.5^o	Year
Wada et al. (2011a)	30	6	8	17	61	2000	0.5^o	Month
This study	**32.1**	**6.2**	**6.0**	**16.7**	**61**	**2000**	**0.5^o**	**Month**
This study	**36.8**	**6.3**	**6.1**	**11.8**	**61**	**2000**	**0.5^o**	**Year**

Table 4.1: Population (100 millions) in 2000 under different degrees of blue water stress

5. Discussion and Conclusions

5.1. Discussion

This study attempted to assess blue water stress, using Water Scarcity Index (WSI), at a monthly temporal resolution on a global scale. PCR-GLOBWB was used to compute blue water availability from the year 1958 to 2001. The global water demand was estimated for the year 2000 as benchmark year by the implementation of approaches used in previous studies (Flörke and Alcamo, 2004; Oki et al., 2001; Siebert and Döll, 2008; Vörösmarty et al., 2000; Vassolo and Döll, 2005; Wada et al., 2011a) with the latest available datasets (livestock, desalinated water use and groundwater abstraction). This study brought together all the latest methodologies and made use of the latest up to date available datasets and estimated blue water scarcity on a global scale taking into account climate variability over a period of 43 years (1958-2000).

For this assessment we estimated the net Industrial water demand for the year 2000, following the methodology of Vassolo and Döll (2005). This methodology allowed us to take into account the recycling ratio of the power plants globally which in return gave us better results regarding the industrial net water demand. Therefore this is the first time that a study estimated the net industrial water demand for the year 2000 by using the latest available datasets and methods and used it to assess the water stress conditions globally. A better estimation of industrial net water demand allowed us to assess water stress in a better way and reveal those regions where industrial activity is high. Also this study revealed those regions globally where the industrial net water demand dominates the total net water demand and this allowed us to investigate which areas are prone to water scarcity due to intense industrial activity. Such regions are Eastern United States of America Northern Europe, Russia and China.

A weakness of the methodology for the estimation of the industrial net water demand is that due to the fact of the lack of data, we did not manage to examine the variation of the industrial net water demand within the year but we assumed it to be constant throughout the year. We would have been able to estimate industrial net water demand on a monthly temporal resolution if we could obtain data concerning the energy production of each power station or of each country and by doing so we would have assessed water stress conditions in a better and more detailed manner. Unfortunately data of this nature are available only for the United States of America. Another weakness of the methodology for the estimation of the net water demand and the gross water demand of the thermal power generation is that it is dependent on available water resources and it is possible that the power station are not properly aligned with the drainage network and this could affect this analysis by giving false results in some cases.

At present most studies, like this one, related to global water stress assessments, use a spatial resolution of 0.5^o due to lack of gridded climatic data in higher resolution and consequently this leads water availability to be estimated with the same resolution. Douglas et al. (2006) showed that the degrees of water scarcity are subject to change depending on different spatial resolution. This makes important the issue of the spatial resolution and scientists have to study this issue even further in order to produce results even closer to reality and with finer temporal and spatial resolutions. Another important issue besides the quality of the various datasets is their availability as well. Governments, organizations and companies should provide the scientific community with the latest available datasets in the minimum cost. Additionally they should try to build better databases with finer resolution. For example for this study if we had in our hands monthly data regarding the energy production of each power plant or of the countries for the year 2000 and the production volume of each country, this assessment would have given better results.

5.2. Conclusions

Previous assessments on water stress (Alcamo and Henrichs, 2002; Arnell, 2004; Kundzewicz et al., 2007; Oki et al., 2001; Vörösmarty et al., 2000) showed that arid and semi-arid regions globally are those which are the most vulnerable to experience scarcity due to limited water resources as an effect of climate variability. Our results agree with the results of those studies but besides the regions vulnerable to water stress conditions due to climate variability, we revealed those areas vulnerable to water stress due to high water demand or limited available water resources. Besides the spatial variability of high water stress we estimated as well the temporal variability throughout the year.

This study assessed the variation of the population which experienced different degrees of water stress throughout the year 2000 and the results showed that the months that the most people (approximately from 1.7 billion to 1.9 billion people on an average annual course) experienced high degrees of water stress are January, February, March and May. According to the results of this assessment, about 1.67 to 2.27 billion people of a total of 6.1

billion people experienced moderate to high water stress conditions in 2000. Our results were compared with the results of similar studies and they agree well with a small deviation. We found out that about 0.21 billion less people live under moderate or high water stress conditions compared to the results of Wada et al. (2011a). This deviation can be explained by the fact that we used different approaches to estimate industrial water demand and the most up to date datasets available for the calculation of desalinated water use and groundwater abstraction.

This assessment also revealed those regions globally which in the year 2000 experienced high water stress. In January the regions which suffered from high water stress (WSI>0.4) are located mostly in parts of North India, East Australia, Central Asia and Central Africa. The situation in February stayed the same but regions in Southern India, West Australia and East Asia showed the same behavior like the rest regions in January. March and April of 2000 are months that high water stress occurred in the western parts of India, East China and Central Africa. Western parts of North America dealt with high water stress in several months of that year (May, June, July and August). In the summer months (June to September in the Northern Hemisphere and December to March in the Southern Hemisphere) regions located around Mediterranean Sea (Spain, Italy, Greece, Algeria and Morocco), North India, Pakistan and East China face high water stress conditions. In the rest months of the year the problem of high water stress was visible in South Africa, central parts of South America, East Europe and East Asia (regions in China and Mongolia). The magnitude of water stress varied both in space and in time throughout the year due to the seasonality of both water availability (e.g. river discharge) and water demand (irrigation and domestic).

In this study we also assessed the WSI on an annual temporal resolution and the results show that there is a difference of magnitude of WSI when we are using different temporal resolutions. In our case we can identify regions where the assessment of annual and monthly water stress was mismatched (figure 4.1). For instance regions such as East Mongolia, North China, western parts of India and Pakistan, Kazakhstan, East Australia, West United States of America and finally central and southern parts of Africa show the highest differences in magnitude, which vary from 0.4 to 1 degrees. This difference in magnitude may arise in these regions due to constant population growth as well as due to climate change.

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Appendix A- Additional Figures of Water Stress

Monthly Blue Water Stress

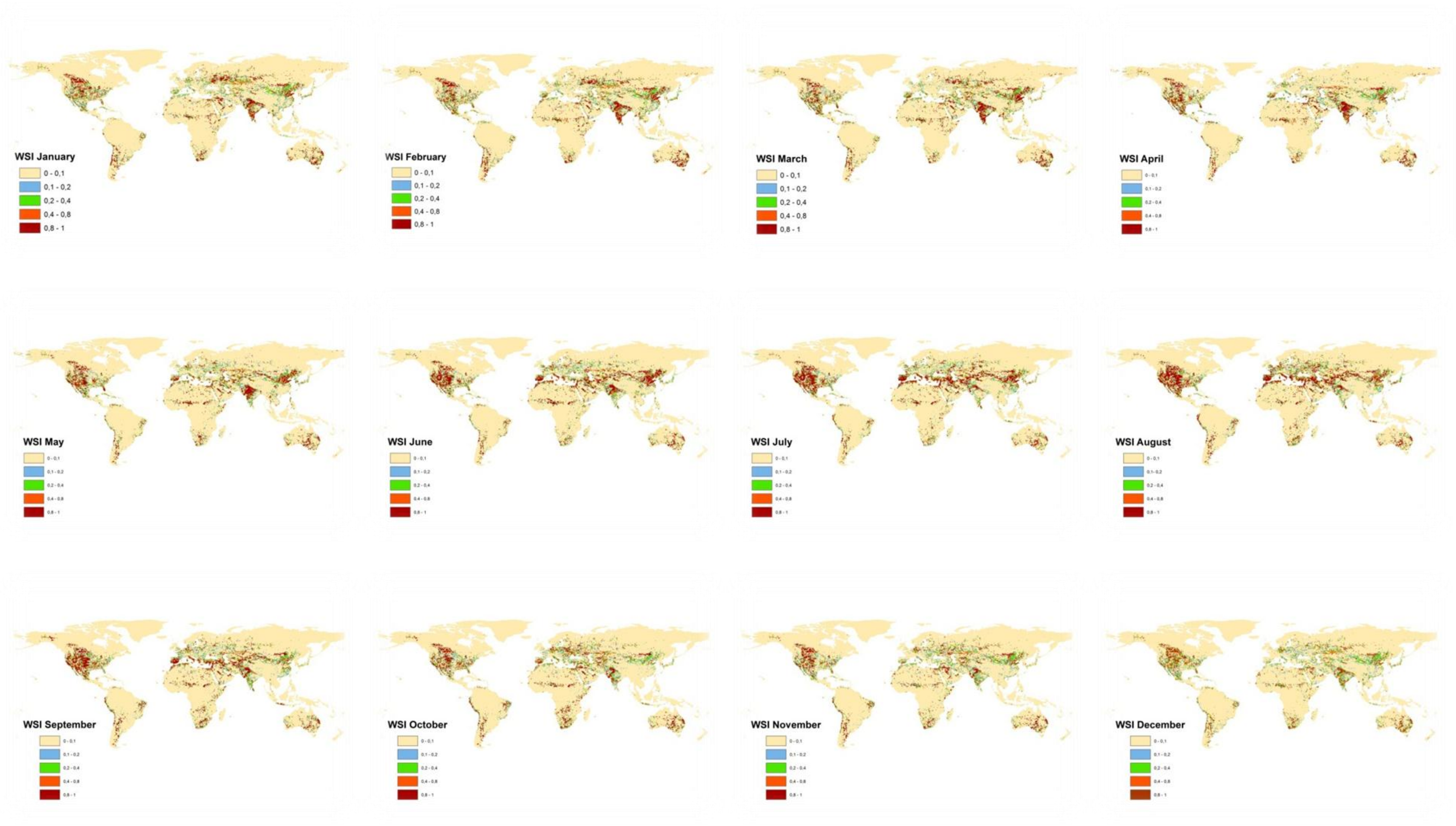

Figure A.1 Monthly blue water stress in the year 2000