WATER RESOURCES RESEARCH, VOL. 41, W04010, doi:10.1029/2004WR003360, 2005

Global-scale gridded estimates of thermoelectric power and manufacturing water use

Sara Vassolo

Federal Institute for Geosciences and Natural Resources, Hannover, Germany

Petra Döll

Institute of Physical Geography, Universität of Frankfurt am Main, Frankfurt am Main, Germany

Received 23 May 2004; accepted 1 February 2005; published 15 April 2005.

[1] New global-scale gridded estimates of industrial water use around 1995 are presented which, for the first time, distinguish between water use for cooling of thermal power stations and for manufacturing. Estimates of annual values of both water withdrawal and consumption are provided with a spatial resolution of 0.5° by 0.5°. Thermoelectric power water use is based on the geographical location of 63,590 thermal power stations. Manufacturing water use is computed by first estimating country-specific water withdrawal values, which are then distributed as a function of city nighttime lights. A comparison to industrial water use in the 50 states of the United States and 89 regions in Russia shows that the developed data set represents thermoelectric power water use satisfactorily, while manufacturing water use remains highly uncertain.

Citation: Vassolo, S., and P. Döll (2005), Global-scale gridded estimates of thermoelectric power and manufacturing water use, *Water Resour. Res.*, *41*, W04010, doi:10.1029/2004WR003360.

1. Introduction

[2] In recent years, there have been various efforts to assess freshwater resources and freshwater use on the global scale [*Shiklomanov*, 1997, 2000; *Vörösmarty et al.*, 2000; *World Resources Institute* (*WRI*), 2000; *Alcamo et al.*, 2003; AQUASTAT, http://www.fao.org/ag/agl/aglw/aquastat/main/index.stmm, accessed 2003]. The primary goal of these efforts has been to evaluate the water availability situation worldwide and thus to identify those countries or river basins that are characterized by water scarcity or predict those that will be in the future. These studies are used by policy makers, nongovernmental organizations, and the interested public to identify the world regions will need more attention and investment to cope with current and future water problems. While global information on water resources is relatively reliable due to measurements of precipitation and river discharge as well as advanced hydrological modeling, global information on water use is generally very poor. Only the U.S. government provides easily accessible information on water use at a high spatial resolution [*U.S. Geological Survey* (*USGS*), 1996]. Most other governments assess water use for the whole country. Additionally, the precise definitions for water uses and water use sectors are not globally consistent.

[3] Industrial freshwater withdrawals account for approximately 20% of the total global withdrawals (70% is used for irrigation). 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, low-income countries only 8% (World Water Assessment Programme, http://www.unesco.org/water/wwap/facts_figures/water_industry.shtml). The importance of knowing the global distribution of industrial water use 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.

[4] Global-scale information on industrial water withdrawal only exists as "total industrial water withdrawals per country" [*WRI*, 2000; *Shiklomanov*, 2000; AQUASTAT, http://www.fao.org/ag/agl/aglw/aquastat/main/index.stmm, accessed 2003], 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. Another important disadvantage of all existing global-scale data sets of industrial water use is that there is no distinction between the fraction of the industrial water use that is used for cooling thermal power stations and the fraction that is supplied to manufacturing. This differentiation is important because the water used to cool thermal power stations, also called thermoelectric power water use, does not lead to chemical contamination of receiving waters, although under certain circumstances the discharge of these waters leads to thermal pollution of rivers (USGS, Water Use Concepts and Terms, http://wa.water.usgs.gov/data/wuse/concepts.htm). In addition, the driving forces of thermoelectric power water use differ from those of the manufacturing sector. This point becomes relevant when assessing future industrial water uses. Differentiated information on the volumes of water

0043-1397/05/2004WR003360$09.00

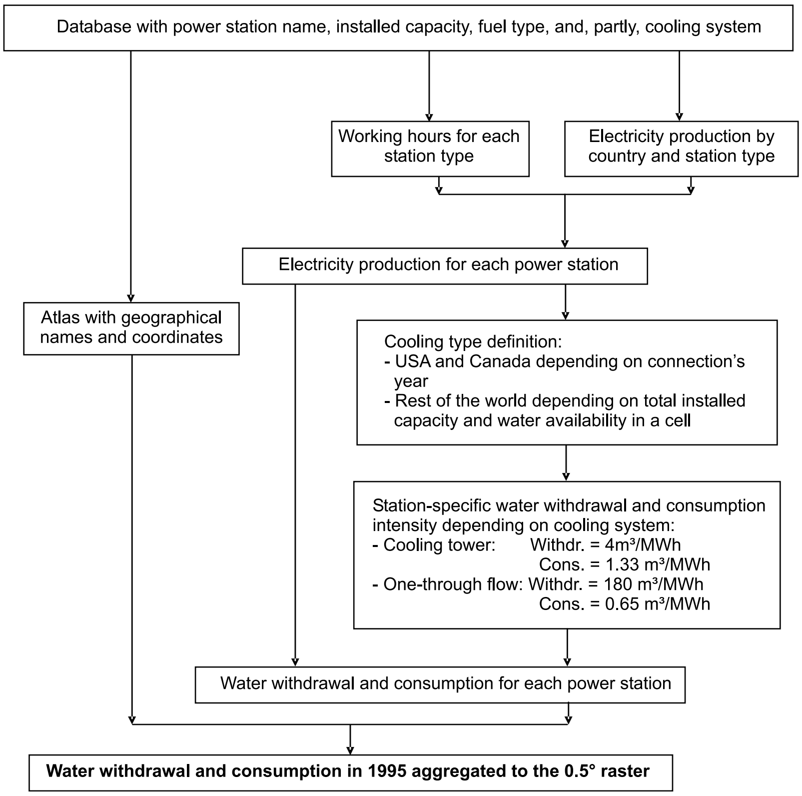

Figure 1. Description of the methodology applied for the calculation of water use for cooling of thermal power stations.

withdrawn and consumed for both cooling of thermal power stations and manufacturing is only available for the United States, where data are published for each county [*USGS*, 1996].

[5] This paper addresses this information gap and presents global-scale 0.5° gridded estimates of industrial water withdrawal and consumptive water use in 1995. These estimates distinguish between thermoelectric power water use and water use for manufacturing (mining is not included), and only consider freshwater uses, as the use of salt or brine water does not influence the terrestrial freshwater cycle. These estimates are an improvement of previously reported estimates mainly because (1) water use for cooling of thermal power plants is distinguished from water use for manufacturing, (2) detailed information on the location and capacity of thermal power plants is taken into account, and the impact of the cooling system on water use is considered, and (3) country values of industrial water use as provided in the literature [*Shiklomanov*, 2000] are checked for plausibility. These estimates will be included in the next version of WaterGAP, a global model that computes water resources and water use at a 0.5° resolution [*Alcamo et al.*, 2003; *Döll et al.*, 2001]. Thus the estimates presented in this paper will contribute to a better assessment of water use and water stress in all large river basins of the globe. They can also be used for developing scenarios of future industrial water use because the algorithms developed to derive water use in 1995 consider the relevant driving forces of industrial water use. Additionally, the estimates on thermoelectric power water use can advance a macroscale assessment of thermal pollution of rivers, as locations and amounts of water discharge from thermal power plants are provided.

[6] Section 2 of this paper presents the methods of computing thermoelectric power water use and manufacturing water use, while section 3 describes the resulting global-scale gridded estimates. In section 4, the reliability of the estimates is discussed, and in section 5 the conclusions of the study are provided.

2. Methods of Estimating Gridded Industrial Water Uses

[7] The global-scale gridded estimates of industrial water use include annual values of (1) thermoelectric power water withdrawals, (2) thermoelectric power water consumption, (3) manufacturing water withdrawals, and (4) manufacturing water consumption in 66,896 0.5° by 0.5° grid cells. All estimates represent the situation around 1995.

2.1. Thermoelectric Power Water Use

[8] Figure 1 provides an overview of the steps followed in the computation of thermoelectric power water use in each 0.5° grid cell. The annual water withdrawal and consumption of each of 63,590 thermal power stations (Figure 2) is estimated first, and the water uses of all stations within the grid cell are then added. The total amount of water withdrawn by each of the 63,590 power stations is computed by multiplying the annual electricity production (MWh/yr) with the water intensity of the power station (water withdrawal per unit electricity production, in

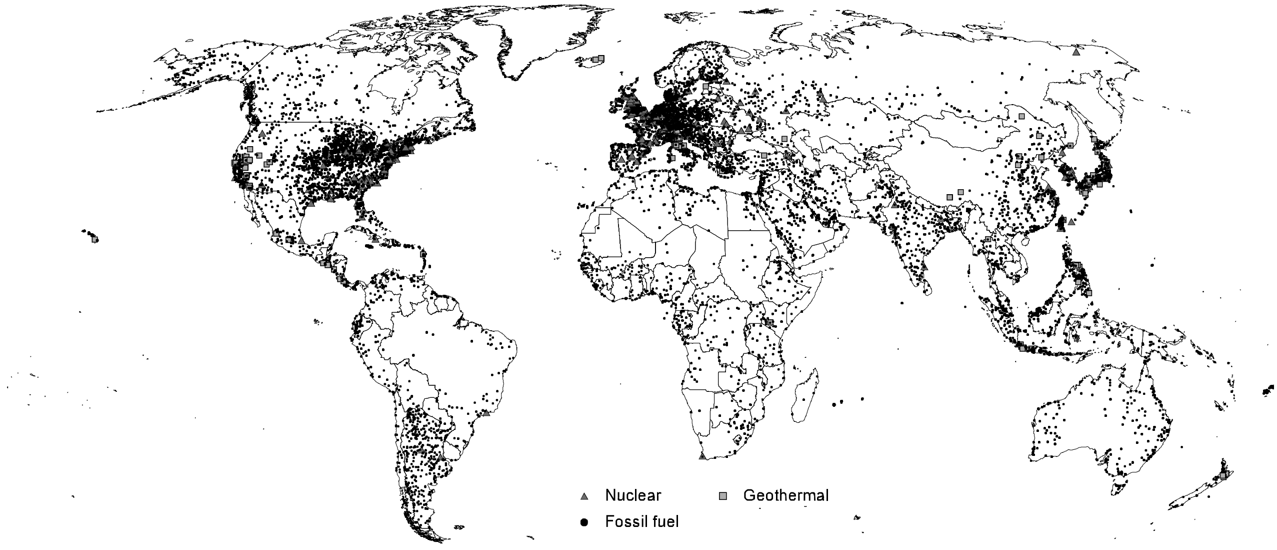

Figure 2. Location of the 63,590 thermal power stations included in the calculation of the new data set. See color version of this figure at back of this issue.

m^3/MWh). The total annual thermoelectric power water withdrawal (TWW, in m^3/yr) in each cell is then calculated as the sum of the withdrawals of all the power stations within the cell as

$$\mathrm{TWW} = \sum_{i=1}^{n} \mathrm{EP_i} \times \mathrm{WI_i}(\mathrm{Cs_i}) \qquad (1)$$

where EP_i is annual electricity produced by a thermal power station i within the cell (MWh/yr), WI_i 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. EP_i in equation (1) represents the driving force for thermoelectric water withdrawal. For deriving estimates of water use in 1995, EP_i was computed based on country values of energy production in 1995 and station-specific information (section 2.1.2). The estimation of WI_i is described in sections 2.1.3 and 2.1.4. The total thermoelectric water consumption is computed in a similar fashion using power station-specific water consumption intensities in equation (1).

[9] By prescribing future trends of the driving force annual electricity production, it is possible to develop scenarios of water use for cooling of thermal power stations. In addition, future TWW scenarios can be derived by (1) including a technological change factor in equation (1) to reflect a decrease of water withdrawal intensity for a given cooling system, (2) changing the cooling system at a certain power plant location, (3) closing down power stations and (4) adding new power stations to a grid cell.

2.1.1. Localization of Thermal Power Stations

[10] The World Electric Power Plants Data Set of the Utility Data Institute (http://www.platts.com, accessed 2000) provides comprehensive global data on all types of electric power stations. The data set contains information on the name of the station, installed capacity, year of connection to the net, fuel type, and cooling type (only for a small fraction of the stations, compare section 2.1.3) as well as other relevant information, but does not include information on the exact geographic location. A total of 63,590 thermal power stations are included in the data set. To determine the geographic coordinates of the stations, the database of foreign geographic features names of the National Imagery and Mapping Agency (Database of foreign geographic feature names, The GEOnet Names Server (GNS), http://earth-info.nga.mil/gns/html/cntry_files.html) was used. This database is a repository of place names comprising some 3.7 million geographic features with their geographic coordinates (decimal latitude and longitude). Because the names of the power stations in the UDI data set generally reflect the name of the places or cities where the stations are located, most of them were allocated via an automated spreadsheet merge. The missing stations were manually allocated to a grid cell. Of the 63,590 thermal power stations, 98% are fossil fuelled, 1% nuclear fuelled, and another 1% geothermal (Figure 2).

2.1.2. Calculation of Annual Electricity Production of Each Power Station

[11] The UDI data set contains values for installed capacity. These values were summed up for each country and compared with published data on total installed capacity for electricity production per country (Energy Information Administration (EIA), International electricity installed capacity data, January 1980 to January 2002, available at http://www.eia.doe.gov/emeu/international/electric.html#IntlCapacity, accessed on 7 March 2005) to evaluate the completeness of the database. This comparison revealed that the installed capacity according to the UDI data set was in the range of ±10% of the EIA country data in 37 out of a total of 92 countries, but was larger for the other countries. These 37 countries, however, account for 72% of the total installed capacity worldwide, as provided by EIA.

[12] The electricity produced in 1995 for each individual station is calculated as the product of the installed capacity and the working hours of the station. The initial estimation of the power station working hours is based on 1997 data published for Germany [*Verwand der Elektrizitätswirtschaft*, 1997], depending on its fuel type (oil, natural gas, coal, lignite, and uranium). The computed electricity productions

are summed for each country and compared with country values of electricity production as provided by the EIA Web site, the International Atomic Energy Agency's database on nuclear power stations (http://www.iaea.org/programmes/a2/index.html), and the *Central Intelligence Agency* [2001]. For each country, the station-type specific working hours were modified such that the electricity produced by the UDI power stations coincides with the country values from the literature.

2.1.3. Definition of Cooling System

[13] 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. Although the system is characterized by very low water withdrawals as compared to the "one-thorough flow" system (45 times less), the water consumption per unit of produced electricity is approximately twice as high as for the "one-through flow" cooling system.

[14] Unfortunately, information on the type of cooling system is available only for 11% of the thermal power stations in the UDI database. However, the analysis of these data allowed the development of two different methods for the estimation of the cooling type system of the rest of the stations. The first, based on information from the United States, is applied to the United States and Canada, while the second, based on information from European countries, is applied for all other countries.

2.1.3.1. United States and Canada

[15] The UDI database provides the type of cooling system for 16% of the 16,590 active thermal power stations in the United States in 1995. However, these stations represent 80% of the total installed capacity of thermal power stations. The analysis of the data shows that the fraction of "one-though flow" cooled power stations has declined steadily since 1970 when the cooling systems in the newly constructed thermal power stations was switched to "cooling towers". To decide on the type of cooling system for the 14,212 power stations without information, annual fractions of each cooling type were obtained based on a statistical analysis of both the cooling system and the year in which the stations with information were connected to the net. Thus the number of each cooling system type was estimated for each year. Each cooling system type was then spatially distributed randomly to all the stations constructed in a given year. This methodology was also applied for Canada, where 1,455 of a total of 1,527 thermal power stations lack information on the cooling system (52% of the thermal power stations' installed capacity).

2.1.3.2. All Other Countries

[16] The historical development of cooling system types in Europe does not show a trend like in the United States and a different methodology had to be developed for this continent. The cooling system data for the Czech Republic, France, Germany, Greece, Ireland, Italy, Portugal, Russia, Spain, and the United Kingdom were analyzed. The hypothesis was 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° cells with low river discharge and high electricity production to prevent excessive warming. The total produced electricity in each cell was plotted against the river discharge as computed by the WaterGAP hydrology model for the climate normal 1961–1990 [*Döll et al.*, 2003]. This plot shows that "one-through flow" cooling systems are mainly installed in cells where electricity production is below 100 GWh/(cell yr) and discharge is larger than 0.3 km^3/yr.

[17] Because of the lack of information on cooling system type for Asia, Africa, Latin America, and Oceania; it was impossible to develop an independent methodology for these continents. The method developed for Europe was tested using data from the Republic of South Africa. It defines all the thermal power stations in the country as equipped with cooling tower, which is accurate. Therefore it was decided to apply the European method for all the countries, except for United States and Canada.

2.1.4. Definition of Water Intensities as a Function of the Cooling System

[18] To define the water withdrawal intensities for each cooling system (in m^3/MWh), data from various power station operators or related authorities were statistically analyzed. The values obtained are (1) 180 m^3/MWh for thermal power stations with "one-through flow" cooling and (2) 4.5 m^3/MWh for thermal power stations with "cooling tower".

[19] The water consumption intensity for each of the two cooling systems was derived from data of *European Commission* [2001] for European thermal power stations as (Figure 1): (1) 0.65 m^3/MWh for thermal power stations with "one-through flow" cooling and (2) 1.33 m^3/MWh for thermal power stations with "cooling tower."

2.2. Manufacturing Water Use

[20] Figure 3 shows how manufacturing water use was computed. First, country values were estimated, which were then disaggregated to the 0.5° grid cells based on city nighttime lights (as described in section 2.2.2). Country-scale data on water withdrawal for manufacturing were only available for United States, Canada and some European countries. However, there is information on total industrial water use for almost all countries [*WRI*, 2000; *Shiklomanov*, 2000]. It is possible to estimate country values of manufacturing water use simply by subtracting the thermoelectric water use calculated here to the published total industrial water use. Yet, country values of total industrial water use may differ appreciably depending on the source of information. Therefore a method was developed to both check the plausibility of the literature data and obtain a best estimate of manufacturing water use per country.

[21] The manufacturing sectors included in the computations are chemicals, paper and paper board, pig iron, fabrics, crude steel, sugar, beer, and cement. The first six sectors are those with the highest water intensities (in m^3 water per ton of product). Sugar and beer are included to obtain manu-

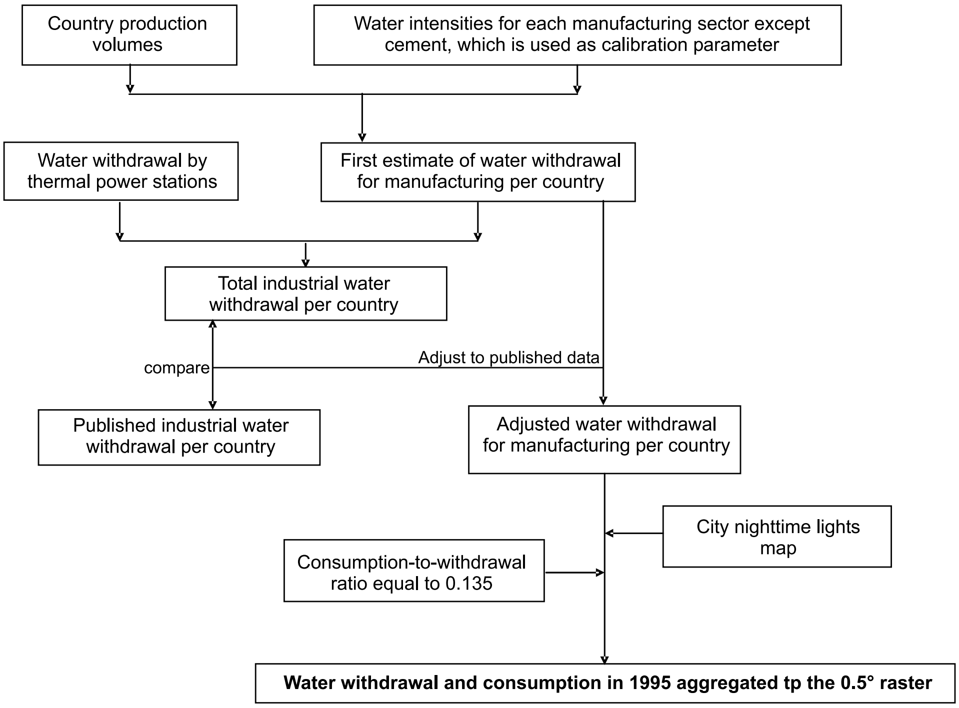

Figure 3. Description of the methodology applied for the calculation of water use for manufacturing. The manufacturing sectors included in the computation are chemicals, pulp and paper, pig iron, sugar, beer, cloth, crude steel, and cement.

facturing water use in very poor countries, where other manufacturing sectors are nonexistent. Cement, which is produced in most of the countries with a wide range of water withdrawals, is included for adjusting the calculations to the most plausible literature data on total industrial water withdrawals (by adjusting its water intensity). However, a further adjustment factor f is required for a number of countries in order to obtain the most plausible literature data.

[22] Country-specific total manufacturing water withdrawal (MWW, in m^3/yr) is calculated as

$$\mathrm{MWW} = \mathrm{f} \times \sum_{\mathrm{i}=1}^{8} \mathrm{VP_i} \times \mathrm{WI_i} \qquad (2)$$

where f is the adjustment factor, $\mathrm{VP_i}$ is the annual production volume of each of the eight manufacturing sectors (ton/yr), and $\mathrm{WI_i}$ is the sector-specific water intensity (m^3/ton). For deriving estimates of MWW in 1995, the driving forces $\mathrm{VP_i}$ and the water intensities $\mathrm{WI_i}$ are defined as described in section 2.2.1. Scenarios of future manufacturing water use can be generated by (1) prescribing the development of the production volumes and (2) including technological change factors in equation (2) to consider a decrease of the sectoral manufacturing water use intensities.

2.2.1. Estimation of Production Volumes and Definition of Sector-Specific Water Intensities

[23] The 1995 production volumes for each of the eight manufacturing sectors in a country were obtained from *United Nations* [1997] and *Central Intelligence Agency* [2001]. Data for typical sector-specific water withdrawal intensities are only available for some industrialized

Table 1. Specific Water Intensity for Various Manufacturing Sectors

Country	Chemicals, m^3/t	Pulp and Paper, m^3/t	Pig Iron, m^3/t	Sugar, m^3/t	Beer, L/L	Cloth, m^3/t	Crude Steel, m^3/t
Canada	345[a]	157[a]	190[a]		9.3[b]		
USA	600[e]	180[c]	86[b]	9[b]	9[b]	200[d]	6[b]
China							56[b]
Japan							56[b]
Austria		150[e]		15[e]	10[e]		15[e]
Belgium					9.3[b]		
Denmark				10[b]	3.4[e]		
Finland		100[b]		10[b]	9[b]	110[b]	
France		150[b]		21[e]	25[e]	110[b]	63[b]
Germany	1200[f]	50[f]	96[f]	10[b]			
Ireland					8[e]		
Israel				2[g]	13.5[b]		
Norway		20[e]			10[e]		30[e]
Russia		223[b]					63[b]
South Africa						350[h]	
Spain		250[e]		3.5[e]	6[e]	8[e]	30[e]
Sweden		20[e]		0.5[e]	4[e]	45[e]	5.3[e]
UK		20[e]		1.5[e]	6.5[e]	110[e]	100[e]
Average	715	120	124	8.3	9.5	133	39

[a] Major Withdrawal Uses of Water from Canada Statistics Web site (http://www.statcan.ca/english/Pgdb/envir05.htm, accessed 2001).

[b] *Carmichael and Strzepek* [1987].

[c] ITT Industries, Guidebook to Global Water Issues (available at http://www.itt.com/waterbook/ind_USA.asp).

[d] U.S. Environmental Protection Agency Web site (http://www.epa.gov).

[e] *European Environmental Agency* [1999].

[f] *Statistisches Bundesamt* [1998].

[g] *Rogers* [1998].

[h] *Lumby* [1999].

countries. Table 1 shows that these figures vary considerably among countries and it is expected that intensities in developing countries might even be outside the given ranges. Because of the lack of data, the mean of the published figures is used for those countries and sectors for which no data are available (Table 1).

[24] Published industrial water withdrawals differ considerably among sources. One might conclude that the *Shiklomanov* [2000] figures are better because they were produced using a consistent methodology, while the *WRI* [2000] data are a compilation of different sources. However, Table 2 shows that the *Shiklomanov* [2000] values of industrial water use also differ from figures published by individual countries. Therefore the manufacturing water withdrawal calculations where adjusted to values from individual country sources when available (Table 2) and, for the rest of the countries, *Shiklomanov* [2000] values were used unless the *WRI* [2000] values appeared more plausible (see below). According to *Carmichael and Strzepek* [1987], water withdrawal intensity for cement varies widely between 50 m^3/t and 900 m^3/t, depending on the technology used and is thus an appropriate adjustment parameter.

[25] From the 160 countries considered, 18 did not have literature values of industrial water withdrawals to tune against and other 7 had thermoelectric power water use larger than the total industrial water use from *Shiklomanov* [2000] or *WRI* [2000]. For these 25 countries the manufacturing water use was calculated in a straightforward manner by just multiplying the produced volumes by the average sector-specific water intensities provided in Table 1 and a value of 50 m^3/t for cement. In addition, 54 countries were tuned using *Shiklomanov* [2000] industrial water use, 11 using *WRI* [2000], and 9 using the country-specific values from Table 2, using a water intensity for cement in the range of 50 m^3/ton to 900 m^3/ton. In the case of the 11 countries tuned using the *WRI* [2000] figures it was not possible to obtain the *Shiklomanov* [2000] values with a water intensity of cement within the prescribed range. The remaining 61 countries were assigned industrial water withdrawals either larger or lower than the published values after the first tuning. A new tuning was the performed, in which the total manufacturing water withdrawal was increased or decreased (as necessary) by 20%. In this case, an additional 31 countries could be attuned to *Shiklomanov* [2000] values, but an even stronger adjustment would be necessary to tune the remaining 30 countries. In 17 of these 30 countries, most of them arid and semiarid countries, the calculated figures were much larger than the published values, and the manufacturing water withdrawal was reduced (by decreasing the tuning factor f in equation (2)) to obtain the most plausible values (*Shiklomanov* [2000] in all cases, except for Zambia, which was tuned to the *WRI* [2000] value as the necessary correction factor was smaller than it would have been to get the *Shiklomanov* [2000] data). Similarly, the total manufacturing water withdrawal was increased in the 13 remaining countries to obtain the most plausible industrial water uses (in 8 cases to *WRI* [2000] and in 5 cases to *Shiklomanov* [2000] values). The case of Israel (for which individual country information was available) is a typical example for arid to semiarid countries, which required a very strong reduction of the average sector-specific water intensities. Therefore the calculated industrial water withdrawals, even with a water intensity of cement of only 50 m^3/ton, resulted in 0.461 km^3/yr, but the records from the country indicate a total of only 0.11 km^3/yr (Dreizin, Water Commissioner of Israel, personal communication, 1998). Obviously, advanced water saving technologies lead to much lower water intensities in Israel than in the generally humid countries for which sector-specific water intensities are available (Table 1).

Table 2. Country-Specific Versus *Shiklomanov*'s [2000] Values of Total Industrial Water Use for 1995

	Country-Specific Values, $\times 10^6$ m^3/yr	*Shiklomanov*'s [2000] Values, $\times 10^6$ m^3/yr
Canada[a]	35,571	39,542
Germany[b]	35,138	32,200
Ireland[c]	250	599
Israel[d]	110	100
Italy[c]	7,980	11,676
Norway[c]	1,378	1,440
Russia[e]	39,500	50,220
Sweden[c]	1,479	1,758
United Kingdom[f]	7,190	21,996
United States[g]	218,608	216,630

[a] Major Withdrawal Uses of Water from Canada Statistics Web site (http://www.statcan.ca/english/Pgdb/envir05.htm, accessed 2001).
[b] *Statistisches Bundesamt* [1998].
[c] *European Environmental Agency* [1999].
[d] Dreizin (Water Commissioner of Israel, personal communication, 1998).
[e] *Goscomstat* [1998].
[f] AQUASTAT (http://www.fao.org/ag/agl/aglw/aquastat/main/index.stmm, accessed 2003).
[g] *USGS* [1996].

[26] To estimate the consumptive use for manufacturing, withdrawal use is multiplied by the manufacturing water use efficiency (consumption-to-withdrawal ratio). Because of the lack of further information, a manufacturing water use efficiency of 0.135 is assumed for all countries, which is the average value for the United States [*USGS*, 1996].

2.2.2. Spatial Disaggregation of Country Manufacturing Water Use to 0.5° Grid Cells

[27] The calculated manufacturing water withdrawal and consumption per country are distributed onto the 0.5° grid proportional to the light intensity of the city lights at nighttime (National Geophysical Data Center, DMSP data collected by U.S. Air Force Weather Agency, http://dmsp.ngdc.noaa.gov/html/download_Night_time_lights_94-95.html, accessed 1998). Each pixel in this city nighttime lights map represents the frequency of occurrence of light in a cloud-free image. It compiles cloud-free nights images taken from October 1994 to March 1995 and has been manually cleaned up of lights from fires, boats in the heavily fished coastal areas, and gas flares. The distribution of manufacturing water use according to city nighttime lights is based on the assumption that industrial activity and thus industrial water use should be somewhat correlated with illumination. For comparison, water use for manufacturing was also distributed proportional to the urban population (as done by *Vörösmarty et al.* [2000] and *Alcamo et al.* [2003]), the brightest city nighttime lights, and the cell

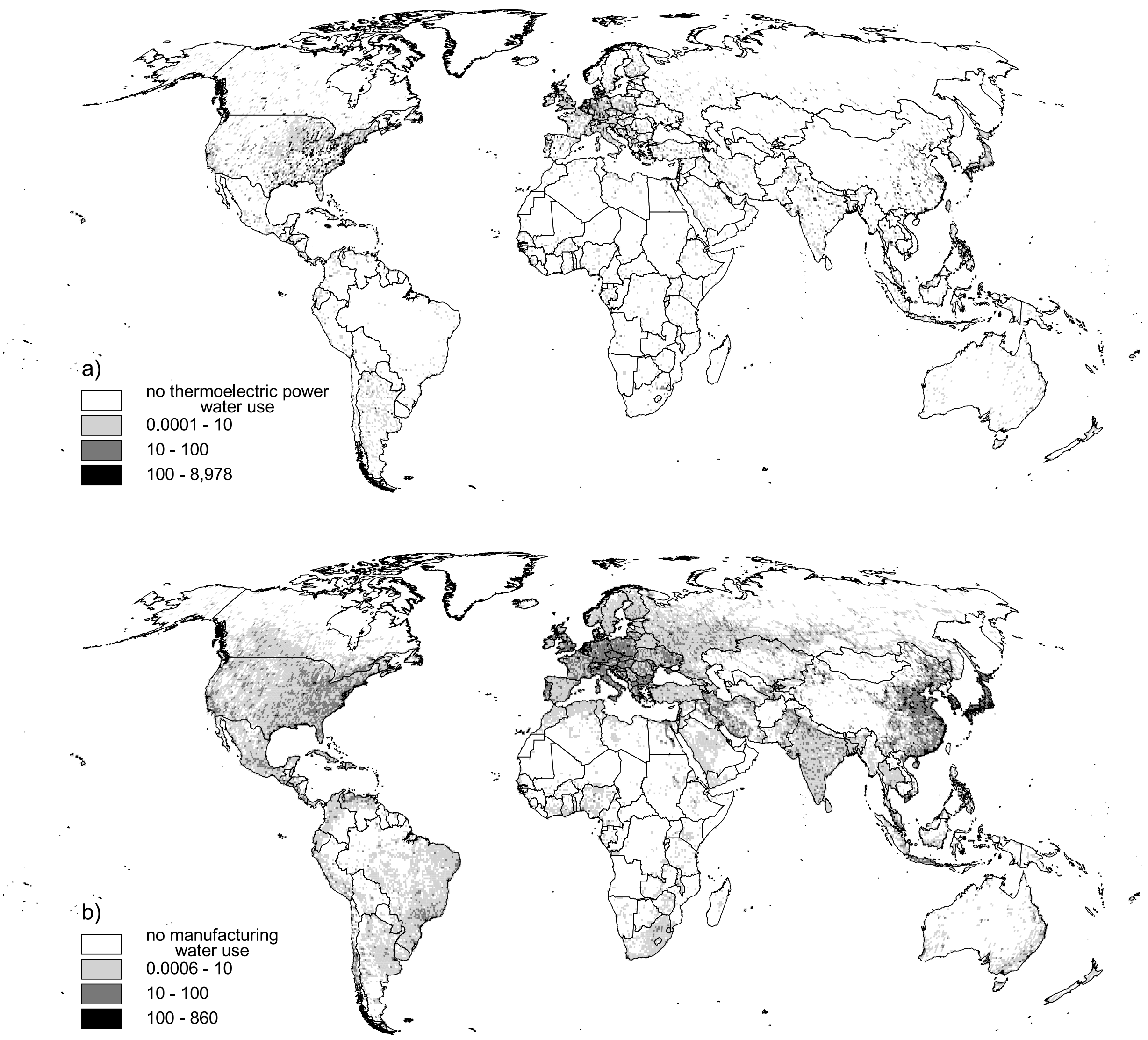

Figure 4. (a) Water withdrawals for cooling of thermal power stations in 1995 per 0.5° grid cell (in million m^3/yr). (b) Water withdrawals for manufacturing in 1995 per 0.5° grid cell (in million m^3/yr). See color version of this figure at back of this issue.

area. The latter represents a spatially homogeneous distribution of the water withdrawal values throughout the country.

3. Results

[28] Figure 4a shows the thermoelectric water withdrawals in 1995. 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 Japan, most thermal power plants are cooled by salt water and thus were excluded from the estimations because this paper only considers freshwater use. In all other regions, thermoelectric water withdrawals are only important in certain industrialized centers (e.g., around Calgary in Canada and along the Ganges River in India). Figure 4b shows the water withdrawals for manufacturing, which are based on distributing country values proportional to city nighttime lights. In the case of manufacturing, the highest withdrawals take place in Europe and eastern Asia.

[29] Figure 5 shows the consumption-to-withdrawal ratio of total industrial water use. For most cells, this ratio lies between 0.1 and 0.25. It is lower in the few cells where water use for one-through flow power stations dominates and is higher where water use for cooling tower power stations are important.

[30] Table 3 summarizes industrial water withdrawal and consumption for each continent. North America has the highest industrial water withdrawal, but most of the used water is returned to the terrestrial freshwater cycle (only 1 million m^3 of water is consumed for every 25 million m^3 of water withdrawn). This is the effect of the numerous thermal power stations with "one-through flow" cooling system in Canada and the United States. In Europe, 12.5 million m^3 of water are withdrawn for each million m^3 of consumed

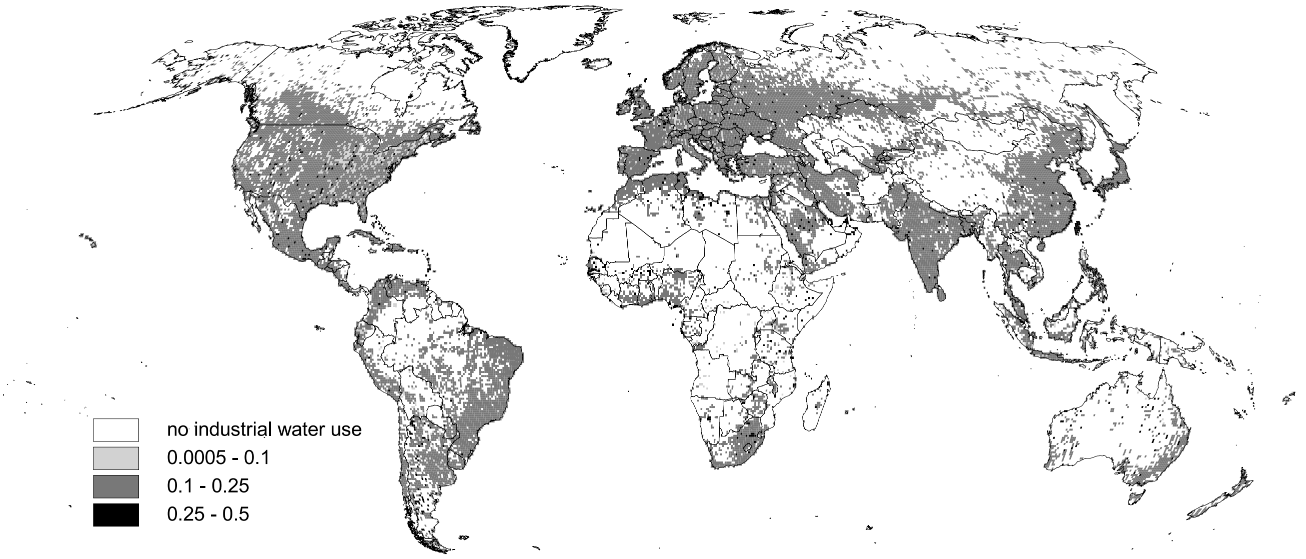

Figure 5. Consumption-to-withdrawal ratio of total industrial water use. The lower ratios correspond to cells in which power stations with "one-through flow" cooling system are predominant. Those cells in which manufacturing is more important are characterized by intermediate values of consumption-to-withdrawal ratios. The highest ratios indicate cells where water use by power stations with "cooling towers" dominates. See color version of this figure at back of this issue.

water. All other continents have lower withdrawal-to-consumption ratios, as thermoelectric power water use by one-through flow stations is not important. The highest thermoelectric water withdrawals occur in North America, followed by Europe. In the case of manufacturing water withdrawals, Asia has the highest figures, followed by Europe. In 1995, 400 km^3/yr are estimated to be globally withdrawn for cooling of thermal power plants and 325 km^3/yr for manufacturing. Water consumption amounts to only 11 km^3/yr (3%) and 44 km^3/yr (13.5%), respectively. This is in stark contrast to irrigation water use, where water consumption is almost 50% of the approximately 2500 km^3/yr withdrawn [*Döll and Siebert*, 2002].

4. Discussion

[31] The new global-scale gridded estimates of industrial water use, with a 0.5° resolution, are mainly based on information that is easily available at the global scale. For consistency, county-specific information on industrial water use in the United States and Russia was not included in the estimations, but was used for their validation. In this section, the reliability of the estimates will be assessed by comparing them with published data.

4.1. Water Use for Cooling of Thermal Power Stations

[32] To validate the methodology for estimating thermoelectric water withdrawals, the computed values are compared with data from the literature for selected countries (Table 4). All literature values are for 1995, except for Canada (1991). The values calculated for United States, Canada, Germany, and Ireland are consistent with the published values. The values for France, Portugal, Spain, and UK differ appreciably, but it is unclear from the literature [*European Environmental Agency* (*EEA*), 1999] whether salt water withdrawals are included in the data. Furthermore, it is unknown if the figures provided by *EEA* [1999] include thermoelectric water use.

[33] A comparison with independent data below the country level is only possible for the United States, where values of thermoelectric water withdrawals in 1995 are provided for each county [*USGS*, 1996]. The data for U.S. states are used to validate the spatial disaggregating of the withdrawals. Figure 6 shows scatterplots for the withdrawals per state (in million m^3/yr) and the specific

Table 3. Summary of Industrial Water Use for Each Continent for 1995

	Cooling of Thermal Power Stations, $\times 10^6$ m^3/yr		Manufacturing, $\times 10^6$ m^3/yr		
	Withdrawals	Consumption	Withdrawals	Consumption	Total Consumption/Total Withdrawal
North America	224,395	3,760	42,526	5,741	0.04
South America and Caribbean	7,308	334	21,394	2,888	0.11
Africa	3,637	344	6,219	840	0.12
Europe	121,789	3,838	96,586	13,039	0.08
West Asia	1,462	159	2,723	159	0.13
Asia	41,033	2,804	149,415	20,171	0.13
Oceania	1,144	168	5,932	801	0.14
World	400,769	11,407	324,793	43,847	0.08

Table 4. Comparison Between Computed and Published Water Withdrawals for Cooling of Thermal Power Stations in 1995 for Selected Countries

	Calculated, $\times 10^6$ m^3/yr	Published, $\times 10^6$ m^3/yr	Calculated/Published, %
United States[a]	187,882	183,396	102
Canada[b]	28,426	28,289	100
Germany[c]	26,345	27,439	96
France[d]	17,944	25,835	69
Ireland[d]	292	277	105
Portugal[d]	449	2,682	17
Spain[d]	3,136	4,909	64
United Kingdom[d]	1,574	1,721	91

[a] *USGS* [1996].

[b] Values for 1991 from Major Withdrawal Uses of Water from Canada Statistics Web site (http://www.statcan.ca/english/Pgdb/envir05.htm, accessed 2001).

[c] *Statistisches Bundesamt* [1998].

[d] *European Environmental Agency* [1999].

withdrawals per state area (in m^3/(km^2 yr)). Model efficiency ME indicates the goodness to fit with respect to the 1:1 line (ME = 1 indicates a perfect fit) and is calculated as

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n} \left(\mathrm{TWW}_{\mathrm{calculated,i}} - \mathrm{TWW}_{\mathrm{published,i}}\right)^2}{\sum_{i=1}^{n} \left(\mathrm{TWW}_{\mathrm{published,i}} - \overline{\mathrm{TWW}_{\mathrm{published,i}}}\right)^2} \quad (3)$$

where TWW is thermoelectric water withdrawal in federal state (million m^3/yr) and n is the umber of states.

[34] ME of thermoelectric power withdrawal per state, in million m^3/yr, is 0.77, while ME of the withdrawals per state area, in m^3/(km^2 yr), is 0.76. It is apparent that both figures are high enough to conclude that the applied methodology for computing spatially distributed thermoelectric power water withdrawals is adequate and leads to a rather low uncertainty. ME of thermoelectric power water consumption per state is only 0.58, and 0.43 for consumption per state area, probably due to the fact that the adopted consumption intensities are lower than the actual values for the United States.

4.2. Manufacturing Water Use

[35] The validation of the spatial disaggregation of country values is performed by comparison with published manufacturing withdrawals in the states of the United States [*USGS*, 1996] and those in the 89 administrative regions in Russia [*Goscomstat*, 1998]. The values for Russia were obtained by subtracting the calculated thermal water withdrawal to the published values of total industrial water withdrawal. Table 5 summarizes the modeling efficiency ME calculated using equation (3) for the withdrawals per area in m^3/(km^2 yr). The first column indicates the values obtained using the distribution to grid cells proportional to the city nighttime lights (based on the National Geophysical Data Center (DMSP data collected by U.S. Air Force Weather Agency, http://dmsp.ngdc.noaa.gov/html/download_Nighttime_lights_94-95.html, accessed 1998) mapping of city nighttime lights). Also presented in Table 5 are the values obtained using three other spatial distribution methods: (1) proportional to the urban population in the grid cell (calculated based on the Gridded Population of the World version 2 from Center for International Earth Science Information Network Web site, http://sedac.ciesin.columbia.edu/plue/gpw/index.html?main.html&2, accessed 2001) and the country-specific fraction of rural population as described by *Döll et al.* [2001]), (2) proportional to the brightest city nighttime lights or, in other words, to the biggest and most luminous spots, and (3) proportional to the cell area. The last alternative means that industrial water use per cell area is constant within a country. The best modeling efficiency for each region is indicated in bold. The model efficiencies for all four disaggregating methods are very low, but the distribution proportional to the city nighttime lights shows the best results, except for the western United States without considering California and Louisiana. Computed consumptive use could be compared only to the U.S. data set. Therefore the results obtained using the distribution proportional to the city nighttime lights are also the best, although the model efficiencies are even lower than those obtained for withdrawals. It appears that the spatial distribution of manu-

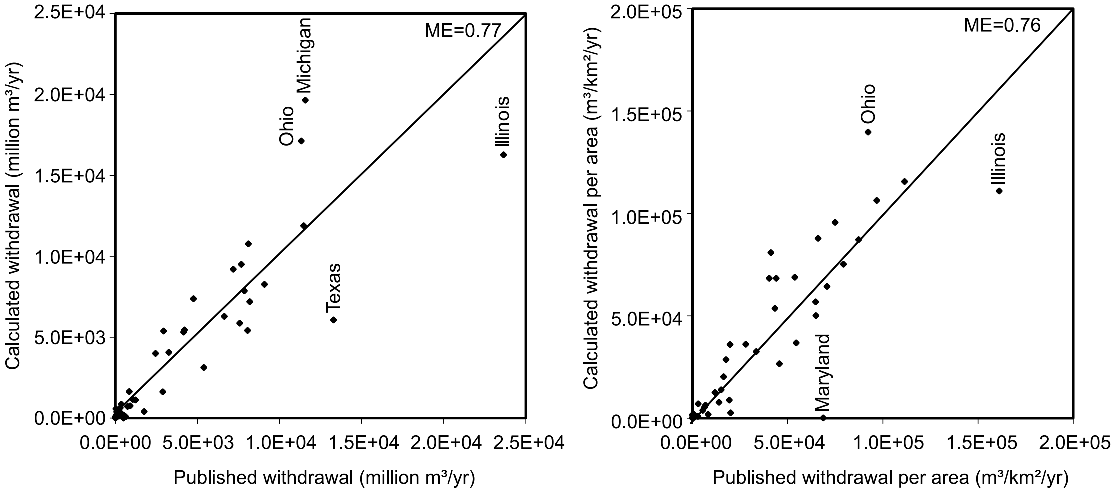

Figure 6. Comparison of calculated and published [*USGS*, 1996] withdrawals for cooling of thermal power stations in the United States.

Table 5. Calculated Model Efficiencies for Manufacturing Withdrawals Per Area in the United States and the Administrative Regions of Russia[a]

	City Nighttime Lights, $m^3/(km^2\ yr)$	Urban Population, $m^3/(km^2\ yr)$	Brightest City Nighttime Lights, $m^3/(km^2\ yr)$	Cell Area
Western United States	**0.24**	0.09	**0.24**	−0.03
Western United States without California and Louisiana	−0.15	**0.61**	0.44	−2.31
Eastern United States	**−0.31**	−4.65	−0.56	−0.54
Eastern United States without Indiana, West Virginia, New Jersey and Massachusetts	**−0.46**	−4.78	−1.72	−0.55
United States	**0.08**	−2.41	−0.56	−0.12
United States without California, Louisiana, Indiana, West Virginia, New Jersey and Massachusetts	**0.13**	−2.23	−0.54	0.03
Russia	**0.64**	−0.38	0.30	−0.03
Russia without Saint Petersburg, Moscow, Ingushetia Republic, Stavropolksy Kray, and Leningradskaya Oblast	**0.21**	−1.42	−0.19	−0.10

[a] The bold values indicate the highest efficiencies for each region. The western United States includes Alaska, Arizona, Arkansas, California, Colorado, Idaho, Iowa, Kansas, Louisiana, Minnesota, Missouri, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. The eastern United States comprises Alabama, Connecticut, Delaware, Florida, Georgia, Hawaii, Illinois, Indiana, Kentucky, Maine, Maryland, Massachusetts, Michigan, Mississippi, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, West Virginia, and Wisconsin. Russia includes 89 administrative regions.

facturing water use cannot be derived well from indicators like city nighttime lights or the urban population. This might seem obvious considering that major water users like paper plants are likely to have rather insignificant nighttime lights and are often located away from urban centers. Even though the model efficiencies are low, the distribution of manufacturing water use proportional to the city nighttime lights provides good results regarding the nondeveloped regions of the world with a low population density, where manufacturing water use is negligible (e.g., northern Canada, Amazon basin, Siberia, and western China).

5. Conclusions

[36] The new global-scale gridded estimates of industrial water use are a first attempt to provide spatially disaggregated information on both water use for cooling of thermal power plants and water use for manufacturing around 1995. These gridded estimates (cell size 0.5° by 0.5°) include both consumptive and withdrawal water uses. 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 and their pollution potential. On the basis of the methods to estimate industrial water uses in 1995, scenarios of future industrial water uses can be derived in a consistent manner because the methods take into account the different driving forces of thermoelectric power and manufacturing water uses. Additionally, the presented estimates on thermoelectric power water use can advance a macroscale assessment of thermal pollution of rivers, as both the location and the volume of discharged water are known.

[37] Because of the inclusion of the specific location of 63,590 thermal power stations, the estimates appear to closely represent the actual water use for cooling of thermal power plants. However, the estimates of grid level manufacturing water use are rather poor for the following reasons: (1) Published data on country-specific total industrial water use, from which the manufacturing water use are derived by means of tuning the model calculations, are rather uncertain. (2) The sector-specific water use intensities are expected to vary considerably among countries but, because of the lack of data, are generally assumed to be constant in this study (except for the few countries for which country-specific information on sectoral water use intensities were available). (3) There is no good predictor for the spatial distribution of manufacturing water use within countries. The consideration of city nighttime lights at least prevents the allocation of manufacturing water use in grid cells without much human activity.

[38] To improve the global picture of industrial water use, it is recommended that water use surveys like those conducted every five years in all counties of the United States [*USGS*, 1996] be carried out. In addition, following the example of the United States, these surveys must be made freely available. Irrespective of the global analysis, such surveys would be a very important basis for river basin management plans and water demand management at the river basin or country level.

[39] **Acknowledgment.** This research was funded by the German Federal Ministry of Education and Research (BMBF 07GWK03 – 203008).

References

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert (2003), Development and testing of the WaterGAP 2 global model of water use and availability, *Hydrol. Sci. J.*, *48*(3), 317–338.

Carmichael, J. B., and K. M. Strzepek (1987), *Industrial Water Use and Treatment Practices*, 123 pp., Tycooly, Dublin.

Central Intelligence Agency (2001), *CIA World Factbook* [CD-ROM], Washington, D. C. (Available at http://www.cia.gov/cia/publications/factbook/)

Döll, P., and S. Siebert (2002), Global modeling of irrigation water requirements, *Water Resour. Res.*, *38*(4), 1037, doi:10.1029/2001WR000355.

Döll, P., J. Alcamo, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert (2001), The global integrated water model WaterGAP 2.1, in *World Water Series*, vol. 5, *EuroWasser*, Cent. for Syst. Res., Univ. of Kassel, Kassel, Germany.

Döll, P., F. Kaspar, and B. Lehner (2003), A global hydrological model for deriving water availability indicators: Model tuning and validation, *J. Hydrol.*, *258*, 214–231.

European Commission (2001), Integrated Pollution Prevention and Control (IPPC), reference document on the application of best available techniques to industrial cooling systems, report, 335 pp., Brussels, Dec.

European Environmental Agency (EEA) (1999), Sustainable water use in Europe. Part 1: Sectoral use of water, *Environ. Assess. Rep. 1*, Copenhagen. (Available at http://reports.eea.eu.int/binaryeenviasses01pdf/en/enviasses01.pdf)

Goscomstat (1998), Environmental protection in Russia, report, Moscow.

Lumby, A. B. (1999), Industry and environment: Clean production and the textile industry in the greater Durban metropolitan area, paper presented at the Economic History Society Conference, Univ. of Pretoria, South Africa, 6–7 Sept.

Rogers, P. (1998), Role of government in regulating industrial water activities, *Background Pap. 16*, Comm. on Sustainable Dev. United Nations, New York.

Shiklomanov, I. A. (Ed.) (1997), *Assessment of Water Resources and Water Availability in the World*, 88 pp., Stockholm Environ. Inst., Stockholm.

Shiklomanov, I. A. (2000), World water resources and water use: Present assessment and outlook for 2025, in *World Water Scenarios: Analysis Global Water Resources and Use*, edited by F. R. Rijsberman, pp. 160–203, Earthscan, London.

Statistisches Bundesamt (1998), Langfristige Entwicklung in der Wasserwirtschaft (1975–1995)–Ausgewählte Ergebnisse, report, Wiesbaden, Germany.

United Nations (1997), *Statistical Yearbook*, Stat. Div., New York.

U.S. Geological Survey (USGS) (1996), Estimated water use in the United States in 1995, report, Reston, Va.

Verwand der Elektrizitätswirtschaft (1997), Stromerzeugung in Deutschland 1997, Infos über Strom—Kraftwerke unterschiedlich genutzt, report, Berlin. (Available at www.strom.de/wysstr/stromwys.nsf/WYSFrameset3?ReadForm&Seite1=/wysstr/stromwys.nsf/Seiten/blanc.html?OpenDocument&Seite2=http://www.strom.de/wysstr/stromwys.nsf/WYSInfoDokumentePunkt2Lookup/8994182969E1136DC1256AD40051F849?OpenDocument&)

Vörösmarty, C., J. P. Green, J. Salisbury, and R. B. Lammers (2000), Global water resources: Vulnerability from climate change and population growth, *Science*, *289*, 284–288.

World Resources Institute (2000), *World Resources 2000–2001: People and Ecosystems: The Fraying Web of Life*, 389 pp., Elsevier, New York.

P. Döll, Institute of Physical Geography, Universität of Frankfurt am Main, D-60054 Frankfurt am Main, Germany.

S. Vassolo, Federal Institute for Geosciences and Natural Resources, D-30655 Hannover, Germany. (s.vassolo@bgr.de)

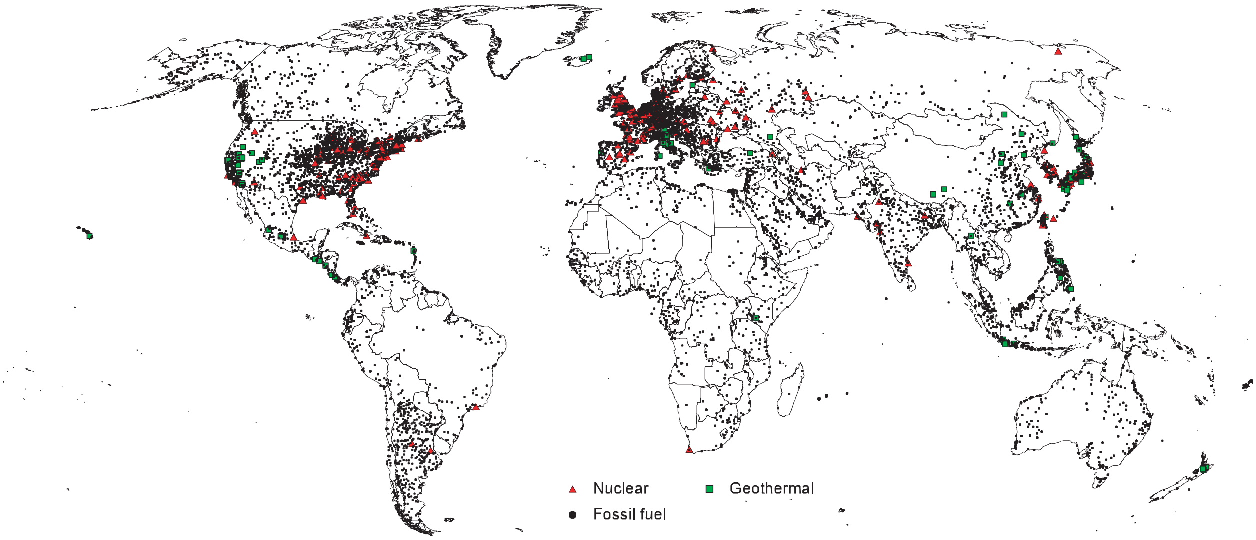

Figure 2. Location of the 63,590 thermal power stations included in the calculation of the new data set.

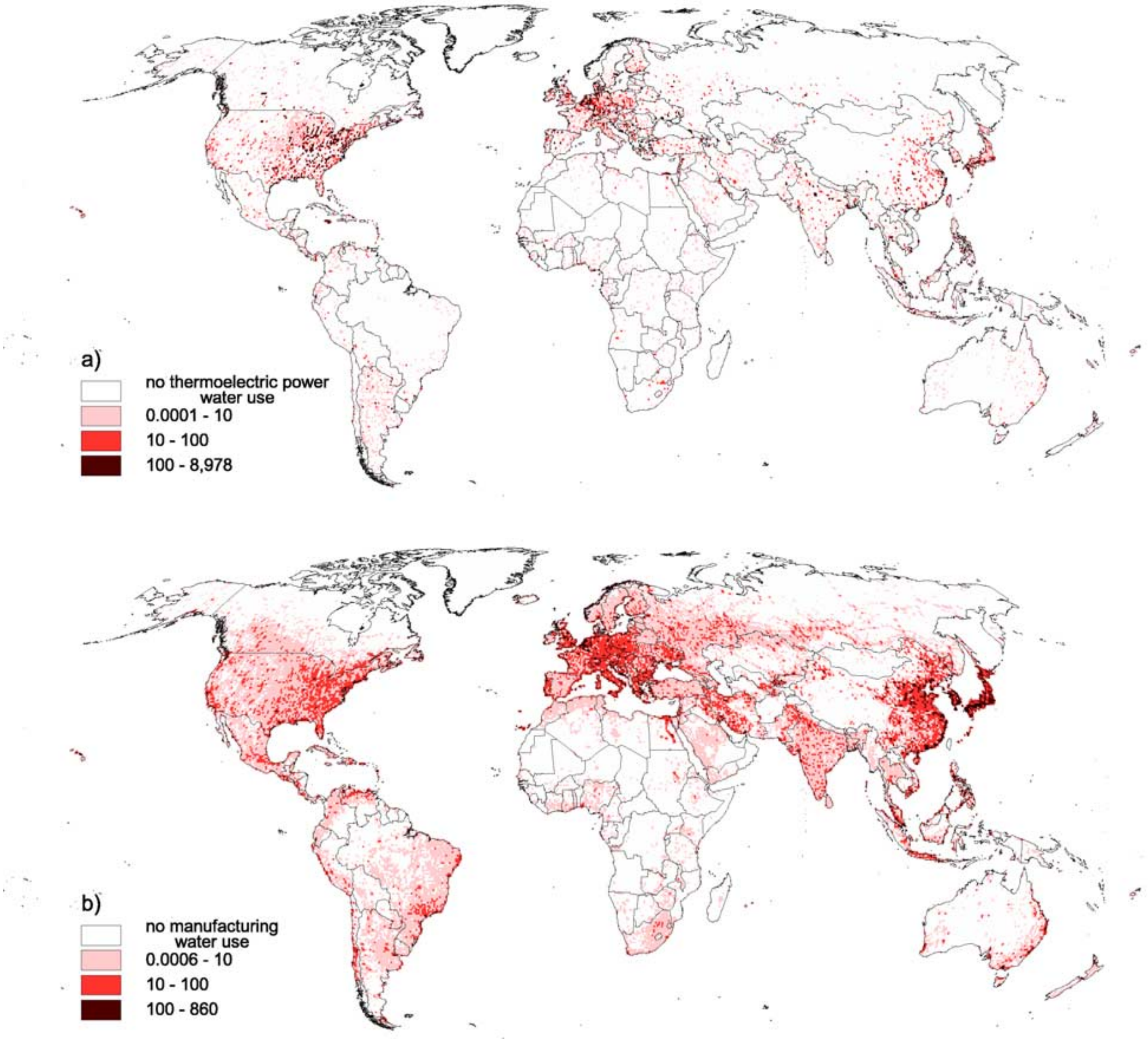

Figure 4. (a) Water withdrawals for cooling of thermal power stations in 1995 per 0.5° grid cell (in million m^3/yr). (b) Water withdrawals for manufacturing in 1995 per 0.5° grid cell (in million m^3/yr).

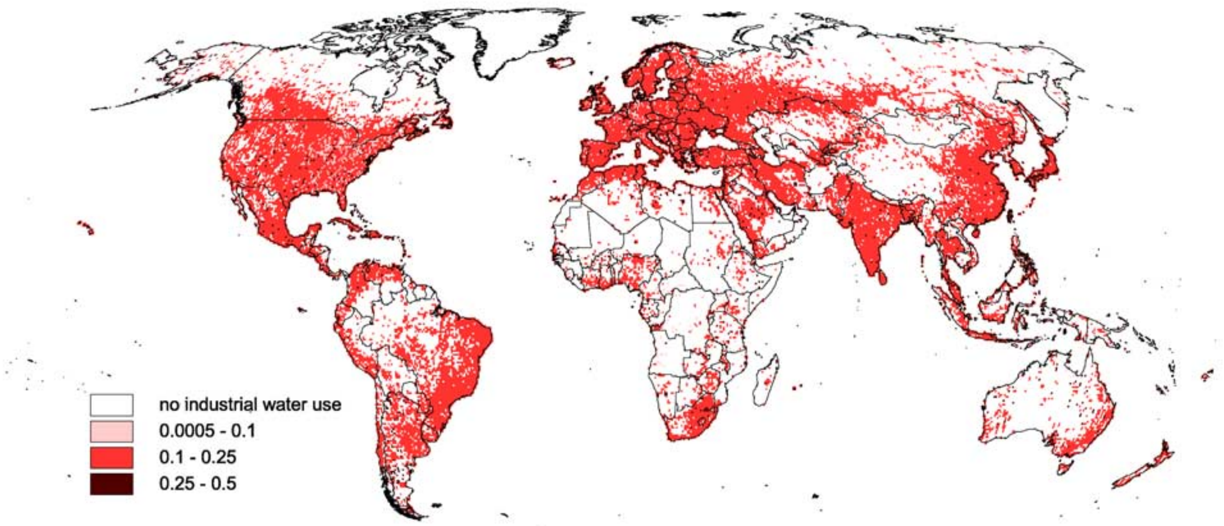

Figure 5. Consumption-to-withdrawal ratio of total industrial water use. The lower ratios correspond to cells in which power stations with ‘‘one-through flow’’ cooling system are predominant. Those cells in which manufacturing is more important are characterized by intermediate values of consumption-to-withdrawal ratios. The highest ratios indicate cells where water use by power stations with ‘‘cooling towers’’ dominates.